AD NUMBER

AD270241

NEW LIMITATION CHANGE

TO

Approved for public release, distribution unlimited

FROM

Controlled: All requests require approval of Commander, Army Natick Research and Development Command, ATTN: DRXNM-TRL. Natick, MA 01760.

AUTHORITY

NARADCOM, DTIC Form 55, dtd 8 Aug 2002

AD 270 241L

DESIGN OF CUSHIONING SYSTEMS FOR AIR DELIVERY OF EQUIPMENT

by Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961

STRUCTURAL MECHANICS RESEARCH LABORATORY
THE UNIVERSITY OF TEXAS
BALCONES RESEARCH CENTER
AUSTIN, TEXAS

DESIGN OF CUSHIONING SYSTEMS

FOR

AIR DELIVERY OF EQUIPMENT

by

Billy C. Ellis
E. A. Ripperger
J. Neils Thompson

Prepared for

QUARTERMASTER

RESEARCH AND ENGINEERING

COMMAND

Contract DA 19-129-QM-1383
O. I. No. 9118

THE UNIVERSITY OF TEXAS

STRUCTURAL MECHANICS RESEARCH LABORATORY

Austin, Texas

August 1961

The Structural Mechanics Research Laboratory

is cooperatively operated by

The Engineering Mechanics and Civil Engineering Departments

at

The Balcones Research Center

University of Texas

Austin, Texas

PREFACE

The air delivery of equipment to combat troops has become commonplace in military tactical operations. There has been a number of general guidance documents in effect in the Army covering technical information and operational air-delivery requirements for military equipment. However, there has been very little information for equipment design engineers to use during the engineering design phase.

The purpose of this report is to describe effective systems by which the impact on ground contact may be reduced within permissible limits through the use of cushioning materials. In addition to theory of cushioning, the properties of cushioning materials, and the fragility of vehicles, this report describes the procedure for designing a cushioning system for a vehicle.

J. Neils Thompson, Director
Structural Mechanics Research Laboratory
The University of Texas
Austin, Texas

August 1961

TABLE OF CONTENTS

Page

PREFACE iii

LIST OF FIGURES. viii

CHAPTER 1

INTRODUCTION

1.1 Air Delivery 1

1.2 Purpose 2

1.3 The Air-Delivery Process 2

Air-transport phase 3

Extraction phase 3

Recovery phase. 3

Ground impact phase 3

CHAPTER 2

STRESS-STRAIN-ENERGY CHARACTERISTICS OF MATERIALS

2.1 Introduction 5

2.2 Definition of Terms 5

2.3 Energy Characteristics 10

CHAPTER 3

THEORY OF CUSHIONING WITH CRUSHABLE MATERIALS

3.1 Introduction 12

3.2 Theory of Cushioning 13

Newton's law 13

TABLE OF CONTENTS
(Cont'd)

Page

3.3 Energy Absorption 14

CHAPTER 4

PROPERTIES OF CUSHIONING MATERIALS

4.1 Introduction 17

4.2 Optimum Strain 17

4.3 Cost Analysis 18

4.4 Efficiency 21

4.5 Paper Honeycomb 22

Stress-strain characteristics 22

Energy absorption 24

Effects of cushion density 24

Effects of moisture 31

Effects of impact velocity 34

Summary 37

4.6 Foamed Plastics 38

4.7 Metal Cylinders 40

4.8 Aluminum Honeycomb 43

4.9 Wood in Lateral Compression 43

4.10 Other Materials 47

TABLE OF CONTENTS

(Cont'd)

Page

CHAPTER 5

FRAGILITY OF VEHICLES

5.1 Introduction 48

5.2 Vehicle Design Considerations 51

CHAPTER 6

CUSHIONING SYSTEM DESIGN FOR A HYPOTHETICAL VEHICLE

6.1 Introduction 54

6.2 Basic Equations 55

6.3 Considerations 56

CHAPTER 7

CUSHION SYSTEM DESIGN FOR SPECIFIC VEHICLES

7.1 Introduction 58

7.2 Cargo Trailer, M101, 3/4-Ton 59

Cushion system development 59

Vehicle and cushion characteristics 66

Design calculations 66

Load spreaders and build-up stacks 68

7.3 Cargo Truck, M37, 3/4-Ton 69

Design calculations 75

Recommended procedure for placing the cushioning. 78

BIBLIOGRAPHY 84

TABLE OF CONTENTS

(Cont'd)

Page

APPENDIX

PROPOSED MILITARY STANDARD - AIR DELIVERY LOADING ENVIRONMENT AND RELATED REQUIREMENTS FOR MILITARY MATERIEL 87

LIST OF FIGURES

Figure		Page
1.1	Extraction Phase	4
1.2	Recovery Phase	4
1.3	Ground Impact Phase	4
2.1	Stress vs Strain for Paper Honeycomb and Felt Shock Pad	7
2.2	Typical Dynamic Stress-Strain Curves of Materials Under Compression Loads	8
2.3	Cushion with Load Applied	9
2.4	Typical Force-Deformation Curve for Cushion Material	9
3.1	Mass Impacting Cushion	14
3.2	Ideal Rectangular Force-Displacement Curve	15
3.3	Typical Stress-Strain Curve for Crushable Cushioning Material	16
4.1	Static and Dynamic Stress-Strain Curves for Paper Honeycomb	23
4.2	Crushed and Uncrushed Paper Honeycomb	25
4.3	Stress vs Strain for Paper Honeycomb with Maximum Strain Varied	26
4.4	Paper Honeycomb - Initial Peak Stress	28
4.5	Paper Honeycomb - Stress at 70 Per Cent Strain	29
4.6	Paper Honeycomb - Energy Absorption at 70 Per Cent Strain	30
4.7	Stress vs Strain for Paper Honeycomb with Varied Moisture and 60 fps Velocity	32

LIST OF FIGURES
(Cont'd)

Figure		Page
4.8.	Energy Absorbed vs Moisture Content for Paper Honeycomb at 60 fps Impact Velocity	33
4.9	Stress vs Strain for Paper Honeycomb with 12 Per Cent Moisture and Velocity Varied	35
4.10	Energy Absorbed vs Impact Velocity for Paper Honeycomb with 10-12 Per Cent Moisture	36
4.11	Effect of Density on the Stress-Strain Curve for Foamed Plastic 108C	39
4.12	Effect of Temperature on Stress-Strain Curve for Foamed Plastic 108C	41
4.13	Thin-Walled Tubes Before and After Dynamic Testing	42
4.14	Force-Strain Curves for Dynamic Tests of Steel, Aluminum and Galvanized Sheet Steel Tubes	44
4.15	Dynamic Stress-Strain Curve for Aluminum Honeycomb	45
4.16	Lateral Compression of Wood	46
5.1	Permanent Deformation Produced by a Triangular-Shaped Acceleration Pulse	49
5.2	Airline Beneath Frame Member on the Water Tank Trailer, XM107E2	52
5.3	Fuel Tank Drain Plug in Easily Damaged Position at Rear of Fuel Tank on the 3/4-Ton Cargo Truck, M37	52
7.1	M101, 3/4-Ton Cargo Trailer	60
7.2	Cushioning Placement and Crushing Areas for a Theoretical 20g Drop for Each of the Three Major Support Configurations Investigated	61

LIST OF FIGURES
(Cont'd)

Figure		Page
7.3	Typical Eight-Point Support Rigging Before Drop	62
7.4	A Typical Before-Drop Rigging with the Three-Point Configuration in Which the Spring Blocks May Be Seen	63
7.5	Rebound of 3/4-Ton Trailer After 40g Impact From Height of 14 ft	64
7.6	Recommended Cushioning Configuration for Unloaded 3/4-Ton Trailer Using 80-0-1/2 EDF Paper Honeycomb	65
7.7	Trailer Rigged for Drop Showing the Configuration Recommended for Dropping the Empty Trailer Using 80-0-1/2 EDF Paper Honeycomb	70
7.8	Trailer After Drop	70
7.9	Cargo Truck, M37, 3/4-Ton	71
7.10	Cushioning Configuration for 3/4-Ton Truck, M37	73
7.11	The 3/4-Ton Truck Rigged for First Drop	74
7.12	The 3/4-Ton Truck Before Drop	76
7.13	The 3/4-Ton Truck After Drop	76
7.14	Using a Keyhole Saw to Cut Out the Crushing Area for the Wheels	79
7.15	Precrushing Honeycomb Around the Wheel Crushing Area	79
7.16	Center Frame Clearing Load Spreader After Drop Allowing Stack to be Removed Before Driving Vehicle Off	82

CHAPTER 1

INTRODUCTION

1.1 Air Delivery

There are a number of general guidance documents in effect in the Army covering technical information and operational air-delivery requirements for military equipment. However, there has been very little information for design engineers to use during the engineering design phase of an end item.

In general, air-drop requirements for an item are given consideration after the test prototypes are completed. This is particularly pertinent to standard commercial items that are procured for military use with little or no modification. Then, by utilizing the available provisions and structural members of the item, supplemented by field modifications with special hardware components and local reinforcements, the item is adapted to the air-drop environment.

It is recognized that economical and operational benefits can be realized by considering the air-drop requirements during design phases of equipment.

Air delivery of equipment to combat troops is a common factor in tactical operations. There are three elements to consider, namely the airdrop of equipment without damage to its effective use; the landing of cargo within a preselected "drop zone"; and in some cases, the airdrop of personnel and equipment at the same rate of descent.

1.2 Purpose

The mission of this report is to describe effective systems by which the impact on ground contact may be reduced to within permissible limits through the use of cushioning materials. The use and arrangement of these materials which dissipate the energy of impact have been termed "systems." They form a method of prepackaging airborn equipment to be airdropped by parachute or parachute combinations. The cushioning systems comprise "crushable" material which absorbs and dissipates the impact energy, but is destroyed in so doing. This type of packaging for airdrop is hence a "one-shot" function system. The basic theory behind the design of such a cushioning system will be presented. Also, information pertaining to the properties of materials which might be used satisfactorily to dissipate the energy resulting from a single-impact load condition, and detailed instructions on how to use energy dissipaters will be provided.

1.3 The Air-Delivery Process

In the process of air delivery, the item to be airdropped is subjected to four different loading environments of which the ground impact is the final and most severe. The data and information contained in this manual have been developed mainly for the protection of materiel (equipment) against ground impact. However, three other loading environments previous to ground impact occur and have a bearing on the package problem. Each successive environment may thus be considered as a phase of air delivery.

Air-transport phase. Depending on the air-delivery system selected, the item will be lashed to an air-delivery platform (a form of pallet), which, in turn, is restrained in the aircraft, or the item is lashed directly to the aircraft floor. During this air-transport period, the item will be subjected to loadings (through its bearing surfaces and tie-down points) from many directions as determined by the maneuvers of the aircraft, and from buffeting during airflight and crash landings.

Extraction phase. This phase describes the withdrawal of the item from the aircraft cargo compartment by the force developed by an extraction parachute, Fig. 1.1. This is connected to webbing around the item, or in the instance of vehicles, to the drawbar or pintle. The extraction force varies from approximately 0.6 to 1.7 times the weight of the item.

Recovery phase. During this phase, the main recovery parachute or parachutes deploy and open, Fig. 1.2. These actions impart high retardation and opening shock forces (up to three times the suspended weight of the item) on the load during the deceleration of the load to terminal velocity. When the terminal velocity is reached, the load on the suspensions is reduced to equal the weight of the suspended item.

Ground-impact phase. The final load environment occurs on the ground impact, Fig. 1.3. To provide the maximum protection to materiel against damage on ground impact, the item can be designed to accomodate energy dissipaters currently in use, or for an item whose design is fixed; the energy dissipaters must be selected to conform as required. Detailed requirements covering the use of energy dissipaters and establishment of tests necessary to determine that the materiel, when used with the dissipaters, will sustain the loading developed on ground impact have been tentatively set out in Army documents.

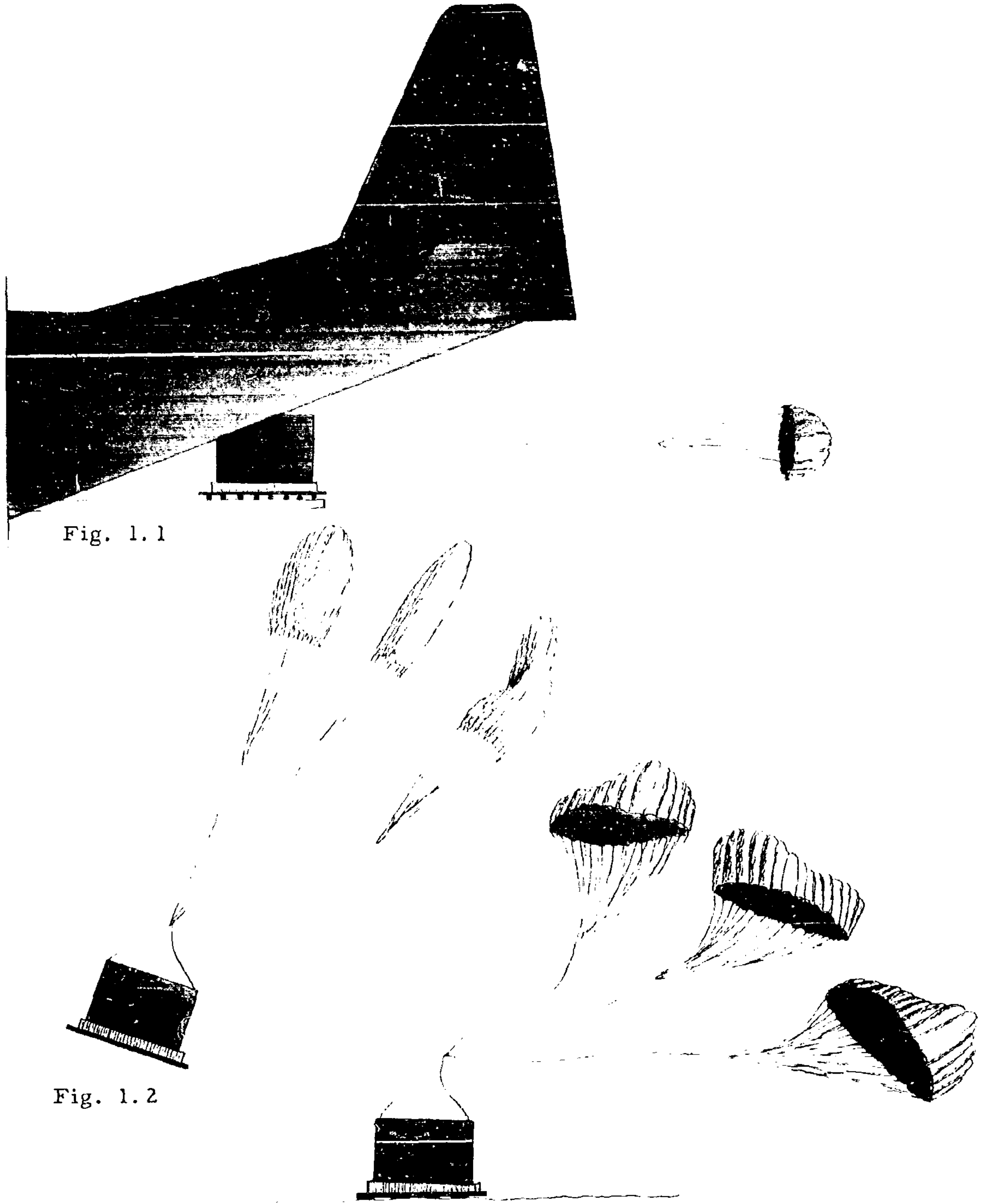


Fig. 1.1. Extraction Phase; Fig. 1.2. Recovery Phase;
Fig. 1.3. Ground Impact Phase.

CHAPTER 2

STRESS-STRAIN-ENERGY CHARACTERISTICS OF MATERIALS

2.1 Introduction

Various characteristic quantities of cushioning materials have been suggested and used during the past few years as criteria of the suitability of such materials for cushioning in the "one-shot" type of service required for air delivery of equipment and supplies. These quantities are generally designated by some descriptive term, or terms, such as efficiency factor, cushion factor, resilience, and energy per crushed volume. While some of these parameters are useful in comparing the suitability of materials for cushioning applications and in design procedures, it is important to recognize that all of the significant characteristics of a cushioning material are indicated by the stress-strain diagram for that material. This curve illustrates in specific form the fundamental behavior of any proposed material, and should be sought as the primary source of information for such materials. It should be noted, further, that such curves are dependent only on the material being tested and not on the item to be cushioned.

2.2 Definitions of Terms

For the convenience of those not familiar with the definitions of stress and strain, these definitions will be repeated here.

Stress, S, sometimes called unit stress, is the value obtained by dividing the load applied normal to the cushion by the face area of the

cushion. Stress is thus the load per unit of face area with pounds per square foot as the convenient unit of measure.

Strain, ε , sometimes called unit strain, is the value obtained by dividing the vertical deformation of the cushion by the original depth. It is a dimensionless number and never exceeds a value of 1.0. Strain is frequently expressed as a percentage. In that case, the maximum value for a cushion being compressed is 100 per cent.

During the deformation of a cushion, there exist corresponding values of stress and strain at each instant during the interval of deformation. If these corresponding stress and strain values are measured simultaneously and plotted, the so-called stress-strain curve is obtained.

Stress-strain curves are shown in Fig. 2.1 for paper honeycomb, a typical crushable material, and for Quartermaster felt shock pads subjected to a dynamic compressive load. The stress is measured in pounds per square foot and the strain is measured in per cent. The area enclosed by the curve indicates the amount of impact energy dissipated by the material, and will be discussed in detail in the next section.

A study of the stress-strain curve for a material reveals much about its ability to carry a given load, to deform under load, and to dissipate energy. Note, in Fig. 2.1, how the difference in energy-dissipation characteristics of the two materials is immediately apparent. Fig. 2.2 shows the stress-strain curves for a variety of materials subjected to dynamic compressive loads. Each material displays different relationships between stress and strain and consequently each has different energy-dissipating characteristics. The comparative

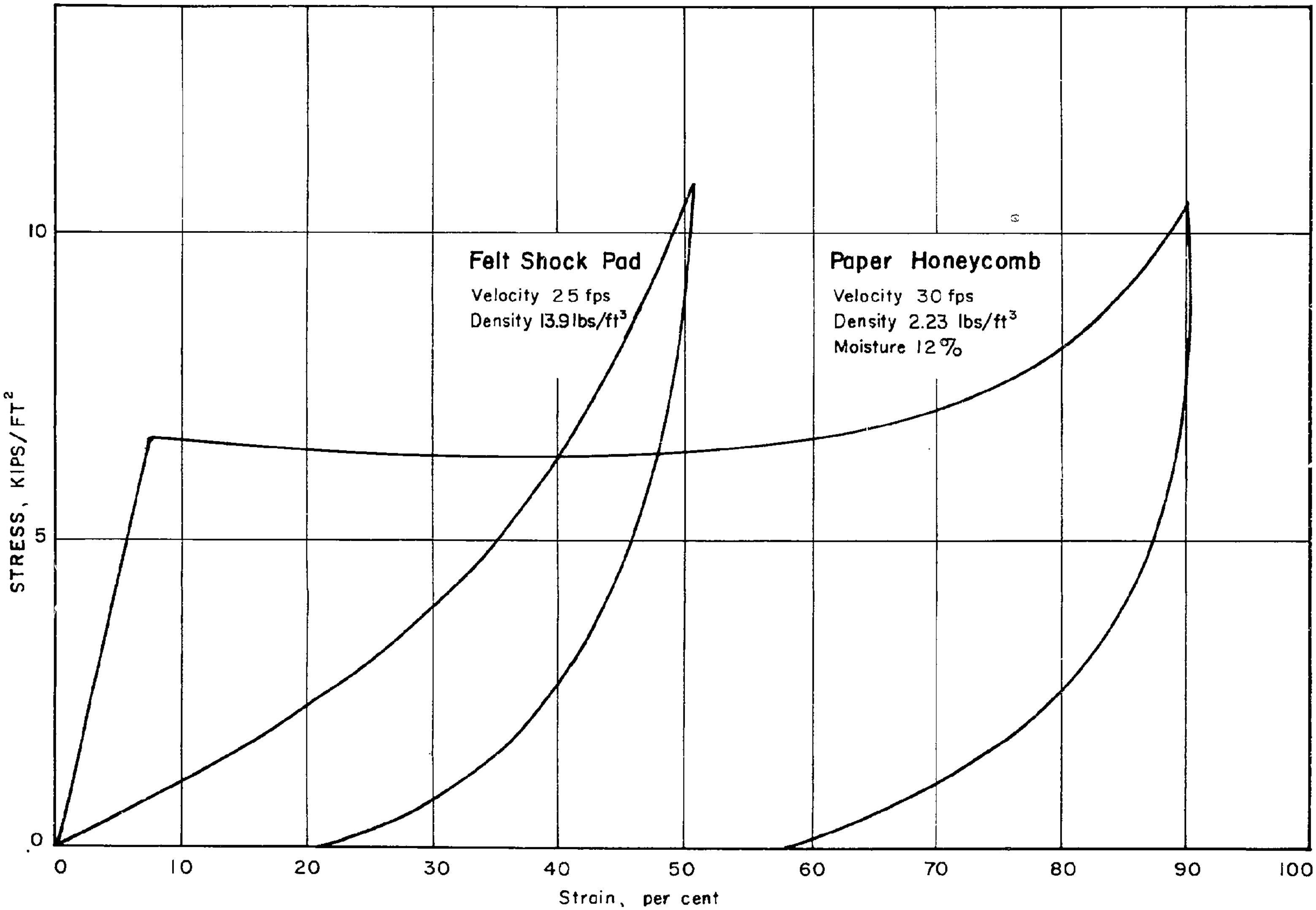


Fig. 2.1. Stress vs Strain for Paper Honeycomb and Felt Shock Pad

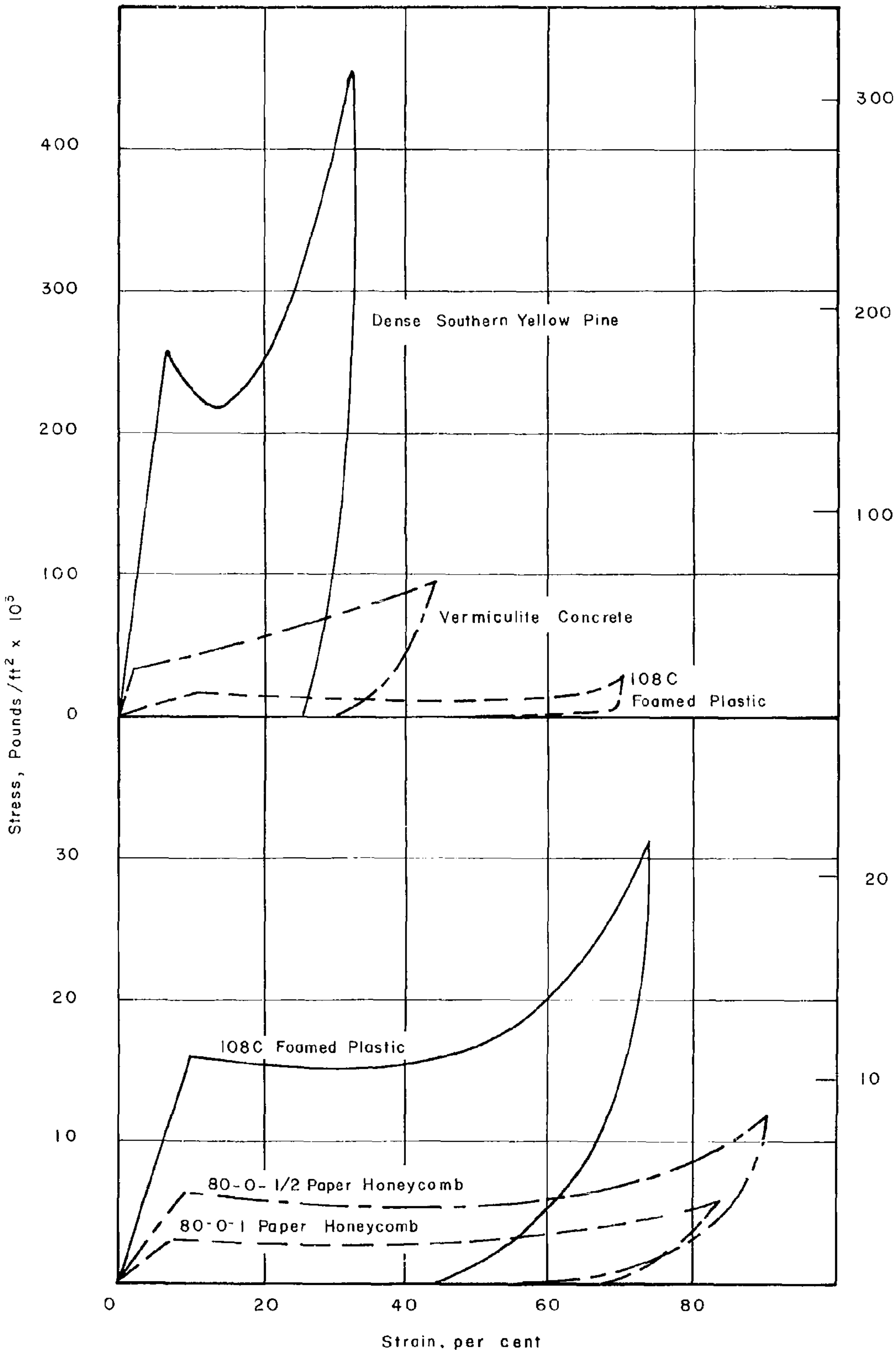


Fig. 2.2. Typical Dynamic Stress-Strain Curves of Materials Under Compression Loads

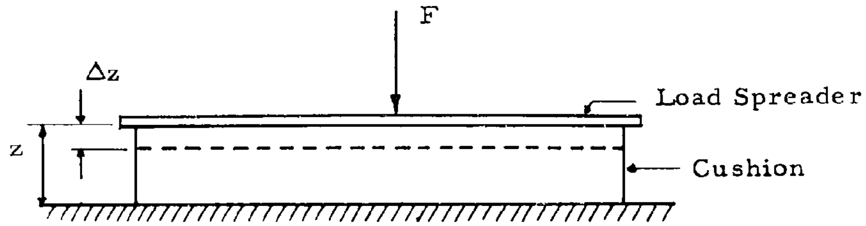


Fig. 2.3. Cushion with Load Applied.

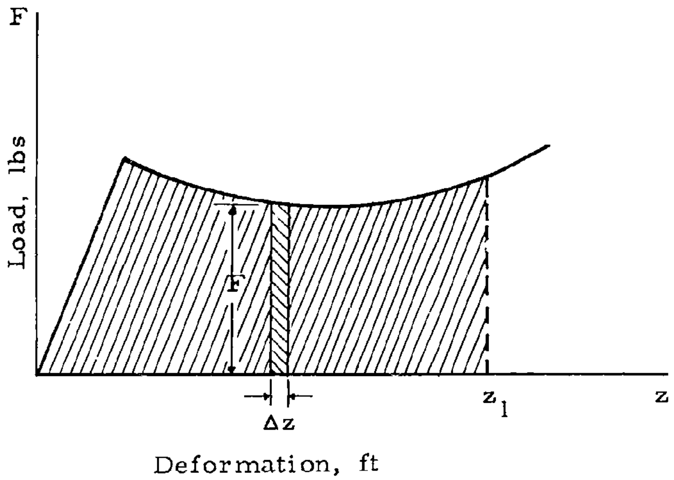


Fig. 2.4. Typical Force-Deformation Curve for Cushion Material.

rebound characteristics and relative energy-dissipating characteristics are readily apparent.

2.3 Energy Characteristics

If an axial load is applied to a cushion, as shown in Fig. 2.3, the cushion will compress some amount Δz. Since work is defined as the product of a force and the distance through which it moves, then work of the amount $F \cdot \Delta z$ will be performed by the force. This work will be absorbed by the cushion as energy of deformation. Fig. 2.4 shows a typical force-deformation curve that might be obtained by progressively loading a cushion and continuously recording the force and deformation. An incremental area under this curve can be represented by $F \cdot \Delta z$, which is the amount of energy the cushion absorbs for the small deformation. The total area under the curve, therefore, represents the total amount of energy which the cushion absorbs during loading. Mathematically this is written as

$$E = \int_{0}^{z_1} F dz \qquad \text{-------- (2.1)}$$

Eq. 2.1 is the total energy absorbed by the cushion as it is crushed to some thickness z_1.

A more useful quantity for comparing cushioning materials is the energy absorbed per unit volume of cushion. This is found simply by dividing the total energy absorbed by the original volume of the cushion.

Then, Eq. 2.1 becomes

$$E_n = \int_o^{z_1} \frac{Fdz}{Az} \qquad \text{- - - - - - - - (2.2)}$$

where E_n is the energy absorbed per unit volume, A is the face area of the cushion, and z is the original thickness.

Since $\frac{F}{A}$ is the unit stress, S, exerted on the cushion, and $\frac{\Delta z}{z}$ is the unit strain, ε_1, which results from the deformation, Eq. 2.2 can be written as

$$E_n = \int_o^{\varepsilon_1} Sd\varepsilon \qquad \text{- - - - - - - - (2.3)}$$

which is the area under the stress-strain curve to some strain ε_1.

If the force, F, is applied for only a short period of time, as is the case when air-dropping supplies, a dynamic stress-strain curve is obtained. This curve is used to obtain the energy-absorbing characteristics of the material when it is subjected to dynamic loads. Examples of dynamic stress-strain curves for various materials are presented in Chapter 4.

CHAPTER 3

THEORY OF CUSHIONING WITH CRUSHABLE MATERIALS

3.1 Introduction

All materials deform to some degree when subjected to load, and consequently are capable of absorbing energy. The amount of energy absorbed depends on the material properties, the rate of loading, the temperature, and other factors. There are many times when it is desirable to recover as much of this absorbed energy as is possible, for instance, when driving a golf ball. However, when cushioning a structure against a sudden impact load, it is often necessary to dissipate this energy in such a way as to prevent damage to the structure.

When a structure is subjected to repeated impact loads, the problem often becomes one of isolation. By the use of spring systems, or resilient materials, it is possible to reduce the impact effect on the structure by reducing the amplitude of the load or by increasing the rise time to peak load; however, there is essentially no dissipation of energy in such a system, and, as a result, the structure often is not protected from all shock loadings.

On the other hand, if a structure is to be protected from only one major shock, a cushioning system can be devised which utilizes a crushable material that dissipates energy by the mechanics of permanent deformation. Air-delivery of supplies presents such a "single-impact" problem. It is reasonable to assume that a cushioning system could be

devised using an inexpensive, crushable material which would be discarded after use.

3.2 Theory of Cushioning[1*]

Newton's law. The relation between the forces applied to a mass and the acceleration of the mass are governed by Newton's law:

$$F_r = Ma \qquad \text{- - - - - - - (3.1)}$$

where F_r = the resultant force applied to the mass in lb,

$M = \frac{W}{g}$ = mass in $lb - sec^2/ft$

W = Weight of the mass in lb

a = Acceleration of the center of gravity of the mass in ft/sec^2

g = Acceleration due to gravity = $32.2\ ft/sec^2$

This equation may also be written

$$F_r = WG \qquad \text{- - - - - - - (3.2)}$$

where

$G = \frac{a}{g}$ = The number of "g's" of acceleration, a dimensionless number.

For example, in Fig. 3.1, if F is greater than W, then the mass is instantaneously being accelerated upward due to the combined forces

---

*Numbers refer to items listed in Bibliography.

of F and W and:

$$F - W = \frac{Wa}{g} = WG \qquad \text{- - - - - - - - (3.3)}$$

or

$$F = SA = W(G + 1) \qquad \text{- - - - - - - - (3.4)}$$

where

S = The instantaneous stress in the cushioning pad in lb/ft^2

A = Effective cushioning area of the pad in sq ft

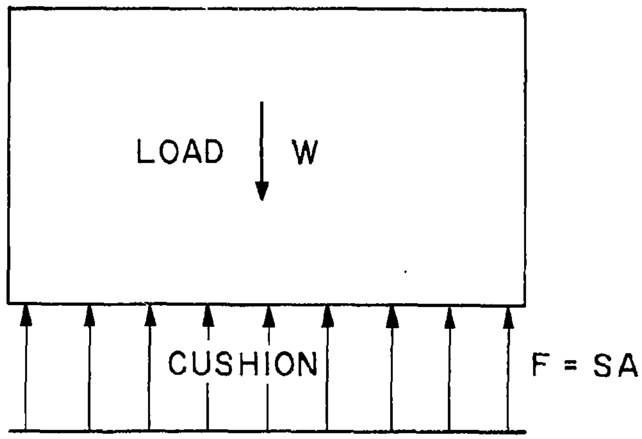


Fig. 3.1. Mass Impacting Cushion

3.3 Energy Absorption.

The energy absorbed by a material or system depends upon two factors; (1) the deformation of the system, and (2) the forces in the system during deformation. The amount of energy absorbed is the product of the average force and the deformation. For any given cushioning problem, there usually is assumed to be a maximum force to which the packaged item can be subjected without producing damage. Thus, two requirements must normally be met by the cushioning system. First, a certain amount of energy must be dissipated. Second, the

maximum force during impact must be kept at or below a given maximum value. Further, in the interest of economy of aircraft space, the volume of cushioning material required should be minimized. These conditions are best met by the "ideal" cushion having a rectangular force-displacement curve as shown in Fig. 3.2.

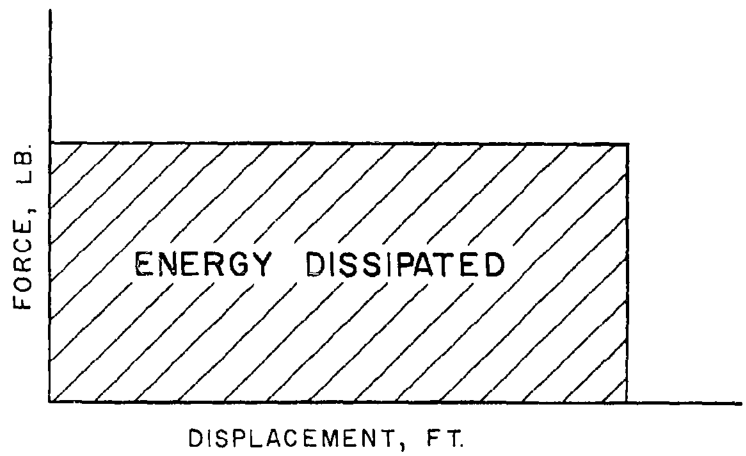


Fig. 3.2. Ideal Rectangular Force-Displacement Curve.

With this ideal material, a constant cushioning force is maintained throughout the impact, and the energy is dissipated with a minimum of displacement. The area under the force-displacement curve, when expressed in ft-lb, is equal to the energy dissipated.

A typical stress-strain curve for cushioning materials, such as paper honeycomb and foamed plastics, is shown in Fig. 3.3. The area under the stress-strain curve represents the energy absorbed per unit volume of cushion as contrasted to the force-displacement curve which gives the total energy absorbed for the complete pad.

It is necessary that careful distinction be made between "energy absorbed" and "energy dissipated." For most cushioning systems, at

least a small amount of the energy which is absorbed by the cushion in the initial impact is retained as elastic energy. This may be returned eventually to the cushioned mass as rebound energy. The energy dissipated during the initial impact is seen, from Fig. 3. 3, to be equal to the energy absorbed minus the rebound energy. The elastic, or rebound energy, is useful in bringing the load to rest during the initial impact, but it is undesirable because of the subsequent rebound of the load. The term resilience is sometimes used in comparing proposed cushioning materials, and has been defined as the ratio of the rebound energy to the energy absorbed. A low resilience is desired.

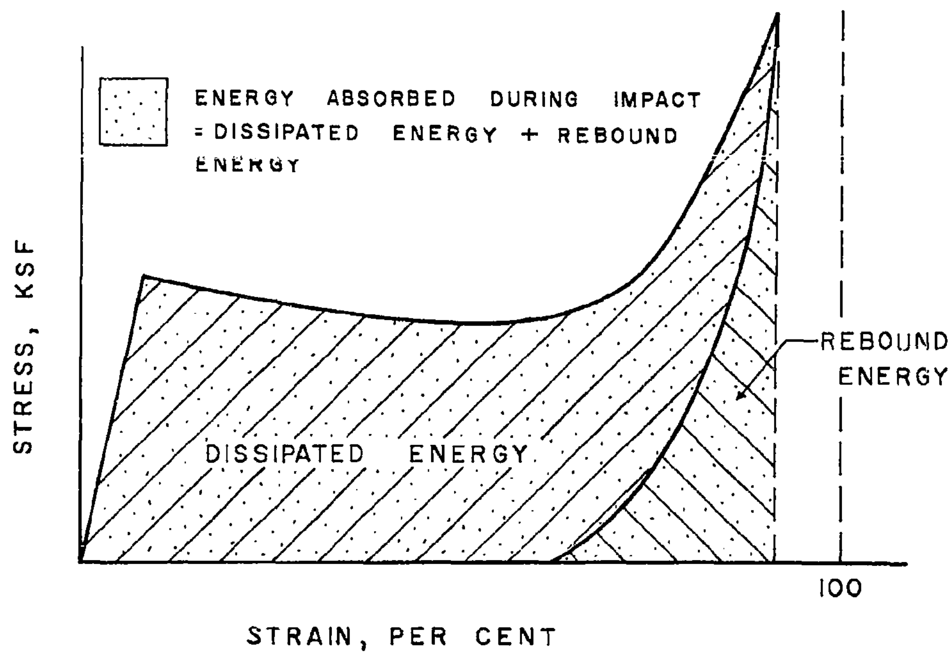


Fig. 3. 3. Typical Stress-Strain Curve for Crushable Cushioning Material.

CHAPTER 4

PROPERTIES OF CUSHIONING MATERIALS

4.1 Introduction

Before a cushioning system can be designed, it is necessary to first know the properties, both static and dynamic, of the materials which will be used. The information which will be of direct importance when choosing a cushioning material for a single-impact-load condition is:

1. Stress-strain curve
   a. Static
   b. Dynamic
2. The energy-absorption capacity
3. Factors which influence the material behavior
4. The maximum allowable deformation, *i.e.* optimum strain
5. A comparison of the different materials on the basis of cost per unit of energy absorbed
6. Efficiency

The last three items can be discussed in general terms that apply to any material, and will be treated first.

4.2 Optimum Strain

The typical stress-strain curve shown in Fig. 3.3 reveals that, although the stress is reasonably constant during crushing, for larger values of strain, the stress begins to increase quite rapidly. This phenomenon is called bottoming. The high stresses associated with

bottoming are usually undesirable, and, therefore, strains should be limited to some maximum value that will provide sufficient energy absorption but keep stresses down to a minimum. The acceleration of the cushioned item may be maintained at a reasonably constant level only if the cushion design does not allow bottoming to occur at impact, thus, some factor of safety must be maintained on the design strain.

An investigation of the dynamic stress-strain curves for different materials indicates that the strain at which the stresses begin to rise sharply is quite often the strain at which the stress becomes equal to the initial peak stress. This is especially true for paper honeycomb and foamed plastics. This suggests that a reasonable "optimum" or design strain might be in the neighborhood of these strain values. For paper honeycomb, the stresses begin to rise sharply in the range from 70 to 80 per cent strain, and the stress rises back up to the value of the initial peak stress at about 70 to 75 per cent strain. This would indicate that an optimum strain would be of the order of 70 to 75 per cent strain. For most of the foamed plastics tested, these values average about 50 to 65 per cent strain. The optimum strain is a somewhat arbitrary number and should be modified for unusual cushioning problems. In any event, it appears that strains much in excess of the optimum strain will only result in high accelerations with little additional energy absorption.

4.3 Cost Analysis[2]

The cost of crushable cushioning material varies, in most cases, directly with the volume required. As a result, determining the volume

of cushioning material required for a given drop is the first step in cost analysis.

In a typical cushioning problem, the following quantities are usually known:

E_n = energy that can be absorbed per unit volume of material in ft-lb/ft^3

S_m = maximum crushing stress of the material in lb/ft^2

W = weight of the cushioned mass in lb.

G_m = specified maximum allowable acceleration of the cushioned mass expressed in multiples of the acceleration of gravity, g. The significance of this parameter and the choice of a value for it are discussed in a later section.

v_1 = velocity at the beginning of impact in ft/sec.

v_2 = velocity at the end of impact in ft/sec.

The following quantities are usually unknown in a cushioning problem:

F_m = maximum allowable force on the cushioned mass in lb.

A = cushion area in ft^2.

z = cushion thickness in ft.

V = cushion volume in ft^3.

The maximum allowable force on the mass may be obtained from the known values of G_m and W, as follows:

$$\left.\begin{aligned} F_m &= W(G_m + 1) \\ \text{Also,}\quad & \\ F_m &= AS_m \end{aligned}\right\} \qquad \text{- - - - - - - (3.4)}$$

It can be seen easily that the total energy absorbed by the cushion is given by the product $V \cdot E_n$.* This energy may be equated to the change in kinetic energy of the dropped mass, i. e.

$$V \cdot E_n = W(v_1^2 - v_2^2)/2g \quad ^{**} \qquad \text{- - - - - - - - (4.1)}$$

Then the volume of cushioning V_u required per unit of weight dropped is

$$V_u = (v_1^2 - v_2^2)/2gE_n \qquad \text{- - - - - - - - (4.2)}$$

The following definitions will now be introduced:

P_c = the cushioning price per unit weight of cushioning material in \$/lb

γ = the density of cushioning material in lb/ft^3

C_c = the cost of cushioning per unit weight of item dropped in \$/lb

Then the cost of cushioning per unit weight of item dropped is given by

$$C_c = V_u P_c \gamma$$

$$= \frac{P_c \gamma}{E_n} \cdot \frac{v_1^2 - v_2^2}{2g} \qquad \text{- - - - - - - - (4.3)}$$

Since the energy absorbed per unit of weight of item dropped is represented by $\frac{v_1^2 - v_2^2}{2g}$, it is seen that the term $\frac{P_c \gamma}{E_n}$ is the cost per unit of energy absorbed, in \$/ft-lb, and is called the cushioning cost parameter. Some typical costs, in \$/ft-lb, for various materials

---

*See Eq. (2.2), Chapter 2.

**The additional potential energy given up by the mass as the cushion crushes is neglected.

Paper honeycomb	- - - - - - -	0.00014
Mild steel	- - - - - - -	0.0000425
Wood in lateral compression	- - - -	0.00003
Foamed plastics	- - - - - - -	0.00015 - 0.0063

The prices quoted are for the cushioning material alone. Mild steel and wood require, in addition to the costs shown, relatively expensive devices in order to utilize the capabilities of the material. Also, cost is only one of the many parameters used in choosing a cushioning material and should not be the sole reason for selecting one material over another.

For a more detailed study of the cost analysis of cushioning materials, the reader is referred to High-Velocity Impact Cushioning, Part II, Energy-Absorbing Materials and Systems.[2]

4.4 Efficiency

There are two efficiency terms which are most commonly used in comparing cushioning materials. The first, suggested by Gretz,[3] is determined only by the shape of the stress-strain curve, and is defined by the ratio of the energy absorbed to a given strain, to the product of the maximum stress, S_m, sustained in the impact, and the strain ε_1, *i.e.*

$$\text{Eff} = \frac{E_n}{S_m \varepsilon_1} \times 100\% \qquad \text{- - - - - - - (4.4)}$$

Any rectangular stress-strain curve, by this definition, results in an efficiency of 100 per cent, regardless of the strain ε_1.

The second, and perhaps more realistic efficiency value, denoted as thickness efficiency, E_z, is based on the assumption that an ideal material that crushes at constant stress, S_m, to zero final thickness has an efficiency of 100 per cent. Thus

$$E_z = \frac{E_n}{S_m \times 1.0} \times 100\% \qquad \text{- - - - - - - (4.5)}$$

The maximum thickness efficiency usually occurs at a value of strain just beyond that which produces a stress equal to the initial peak stress. This value of strain has been referred to as the optimum strain, and, as has been pointed out, the maximum strain should be near the optimum strain. However, a reasonable factor of safety should be maintained to avoid excessive bottoming with the associated high cushion stresses and high accelerations of the packaged item.

4.5 Paper Honeycomb[1]

Many different materials, ranging from popcorn to steel cylinders, have been tested to determine their energy-absorbing capabilities. A selected few will be discussed here with special emphasis on paper honeycomb, which has proven to be quite acceptable in all respects.

Stress-strain characteristics. Typical stress-strain curves for paper honeycomb subjected to dynamic and static loading are shown in Fig. 4.1. The similarity in shape between the dynamic curve and the static stress-strain curve is readily apparent. However, the dynamic stresses and energy-absorption values are considerably higher than the corresponding static values.

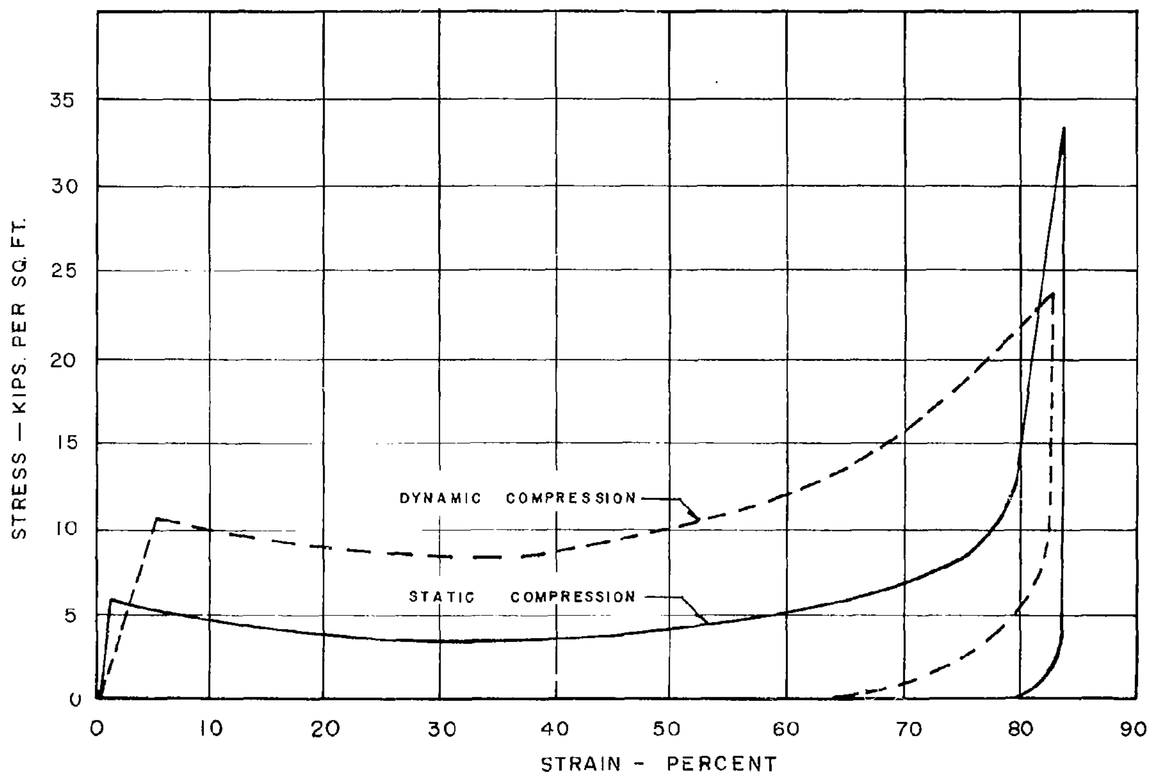


Fig. 4.1. Static and Dynamic Stress-Strain Curves for Paper Honeycomb.

A photograph of uncrushed and crushed paper honeycomb shown in Fig. 4.2 illustrates the manner in which the cell walls collapse to provide an essentially constant crushing stress as shown in Fig. 4.1.

The uniqueness of the dynamic stress-strain curve for paper honeycomb is illustrated in Fig. 4.3. The same impact energy and velocity were used to obtain each curve; however, the thickness of the pad was varied in order to change the maximum strain. The curves indicate that the stress-strain curve for a honeycomb specimen can be found from one test in which the material is completely crushed.

Energy absorption. The energy-absorption values for honeycomb are found by determining the area under the stress-strain curves up to the per cent strain desired. These values are listed in Table I for different grades of honeycomb at a strain of 70 per cent. A study of Table I reveals that the density of the cushion affects the characteristics of the material. The moisture content also has an effect. These two parameters are discussed in more detail in the next two sections.

Effects of cushion density. The effects of the density of the honeycomb cushion on stress levels are illustrated in Figs. 4.4 and 4.5. Fig. 4.6 shows the variation in energy absorption with change in density. The curves indicate that as the density increases the initial peak stress levels increase, as well as stress levels at other values of strain. Also, the amount of energy absorbed increases with increased density.

No appreciable increase in stress level with increase in strain from 70 to 80 per cent was found for the low-density materials. However,

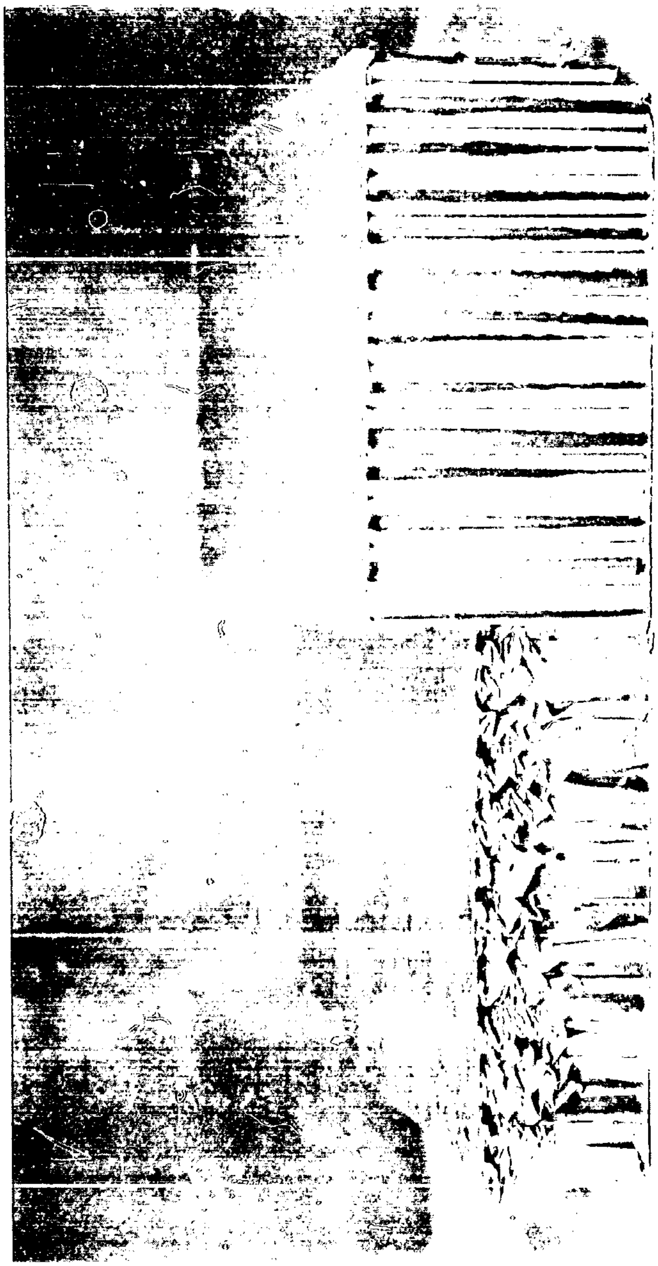


Fig. 4.2. Crushed and Uncrushed Paper Honeycomb

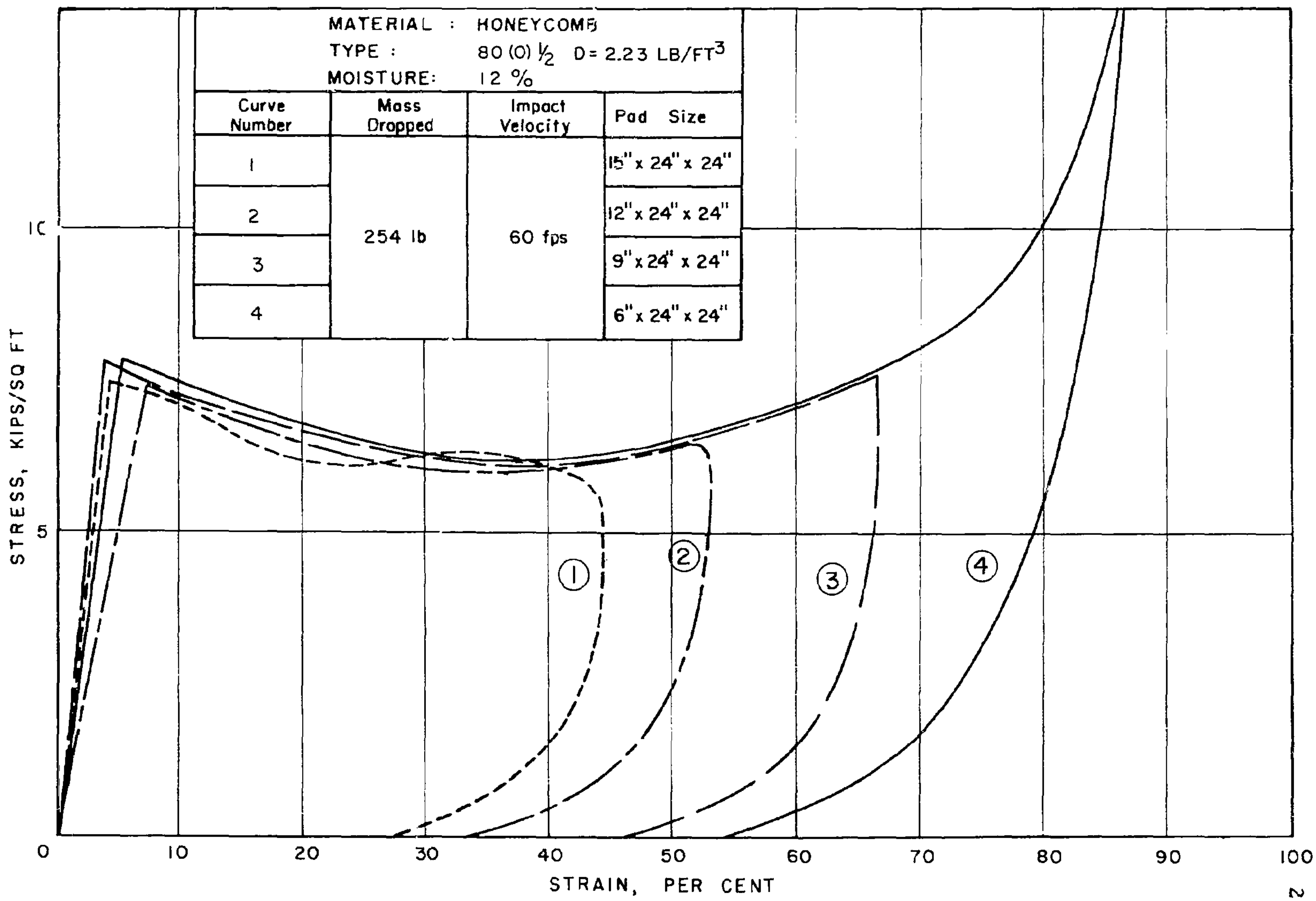


Fig. 4.3 Stress vs Strain for Paper Honeycomb with Maximum Strain Varied

Moisture Content %	Honeycomb Type	Average Dry Density lb/ft^3	Impact Velocity fps	Mass Weight lb	Average Stress to 70% Strain ksf	Total Energy Absorbed to 70% Strain ft lb/ft^3	Maximum Strain %
0	99-0-3/4*	2.12	34	384	6.89	4820	86
			61	240	7.22	5060	89
			87	240	6.66	4660	90
6	99-0-3/4	2.12	33	384	7.30	5100	86
			59	240	7.26	5080	82
			84	178	7.38	5160	84
12	99-0-3/4	2.12	32	384	6.85	4790	83
			57	240	7.03	4920	80
			84	240	7.00	4900	81
17	99-0-3/4	2.12	30	384	5.73	3960	87
			63	178	5.72	3930	84
			89	178	6.10	4170	83
24	99-0-3/4	2.12	29	384	4.92	3450	86
			60	178	5.03	3530	83
			85	178	5.33	3660	82
0	80-0-1/2	2.03	60	230	6.27	4400	92
12	80-0-1/2	2.03	30	476	6.24	4360	93
			60	230	5.67	3980	92
			93	190	5.99	4190	86
18	80-0-1/2	2.03	60	190	5.42	3790	86
24	80-0-1/2	2.03	60	230	4.74	3320	93
1	80-0-1	1.37	60	190	2.75	1930	93
10	80-0-1	1.37	30	190	2.94	2060	85
			62	190	2.82	1980	87
			88	190	2.79	1950	83
15	80-0-1	1.37	60	190	2.75	1920	83
30	80-0-1	1.37	60	190	2.74	1920	83

*First Number = Paper Weight in lb Per Ream, Second Number = Resin Content in Per Cent, Third Number = Cell Size Across Flats, in Inches

Table I. Tabulation of Average Results

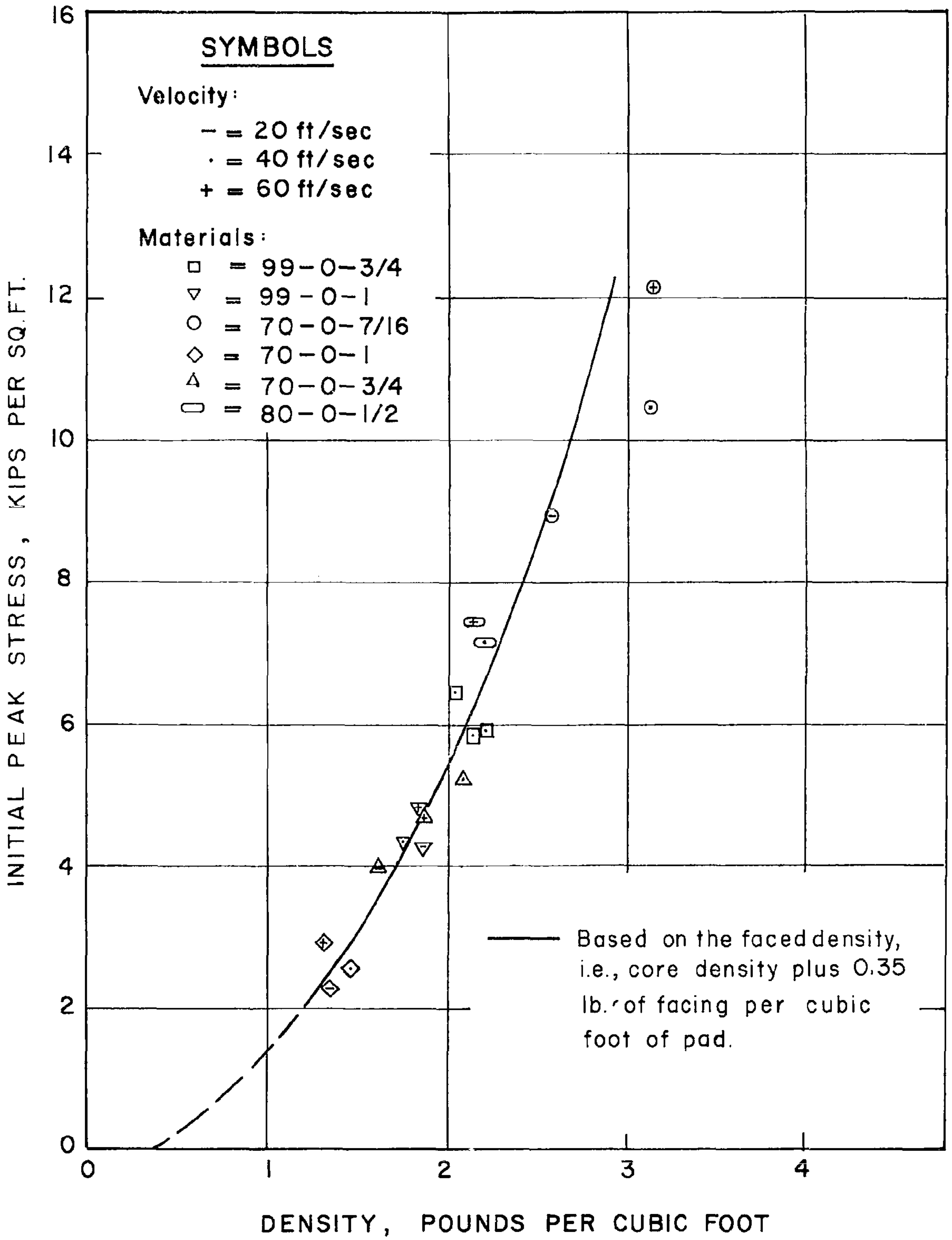


Fig. 4.4. Paper Honeycomb
Initial Peak Stress

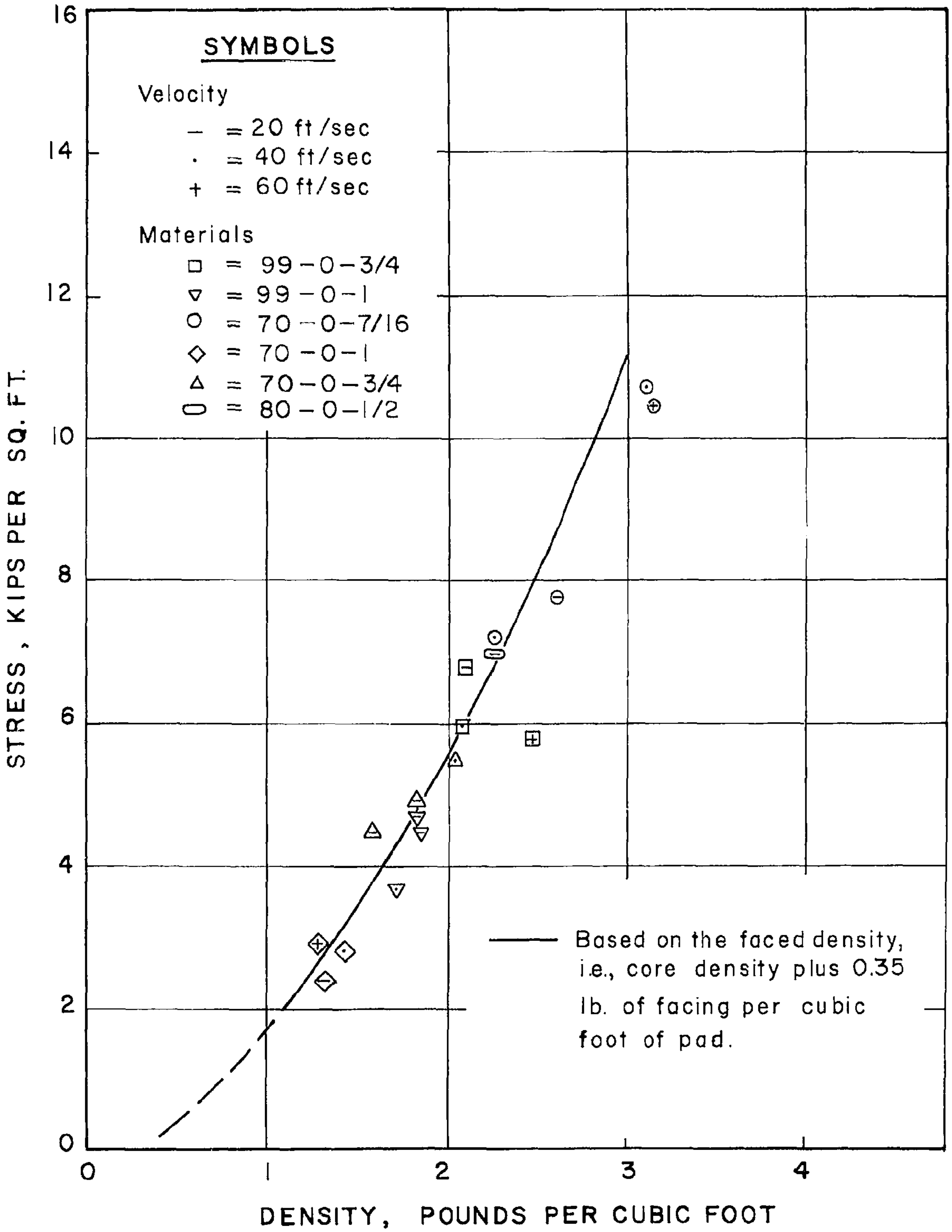


Fig. 4.5. Paper Honeycomb
Stress at 70 Per Cent Strain

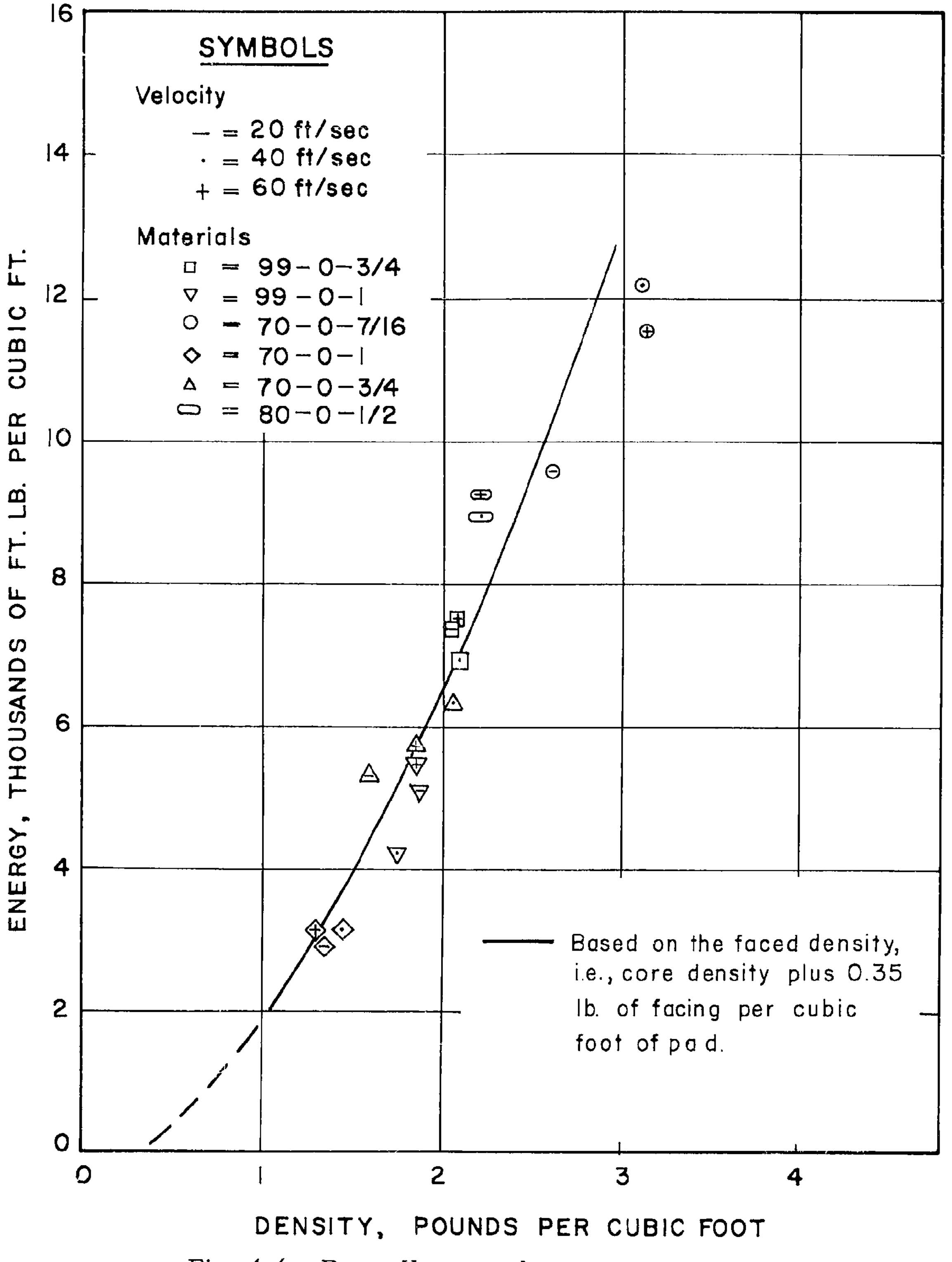


Fig. 4.6. Paper Honeycomb
Energy Absorption at 70 Per Cent Strain

as the density increases, the increase in stress above 70 per cent strain becomes significant. It appears, then, that the lower density materials should have a slightly higher optimum strain than those of higher density.

While strain values of 70 per cent have been used in Table I, it is not to be assumed that higher strains are unacceptable. If the packaged item can withstand the accelerations associated with the higher stresses occurring at, say, $\varepsilon = 85$ per cent, the resulting increase in energy-absorption capacity may justify using this value as the design strain. However, it appears that for most practical purposes, 80 per cent strain is probably the upper limit, with 70 per cent being a more desirable value if some factor of safety against bottoming is to be provided.

Effects of moisture[4]. When using paper honeycomb under field conditions, it is likely that some moisture will be absorbed by the material. The effect of moisture content on the stress-strain characteristics of 80-0-1/2 honeycomb is shown in Fig. 4.7 and the change of energy-absorbing ability of three grades of paper honeycomb with increase in moisture content is indicated in Fig. 4.8. It is evident, at least for the denser grades, that there is some moisture content above which the characteristics of the material are altered.

Although the energy absorbed does begin to decrease after some transition moisture content is reached, the conditions to which the honeycomb must be subjected in order to reach a higher moisture content must be considered. It has been shown by Forest Products Laboratory[5] that paper honeycomb must be exposed to an atmosphere of 80F and 90 per cent relative humidity for 14 days to reach a moisture content of 20 per cent. It will attain a moisture content of 17 per cent when exposed to these conditions for two days. When exposed to 80F and 65 per cent

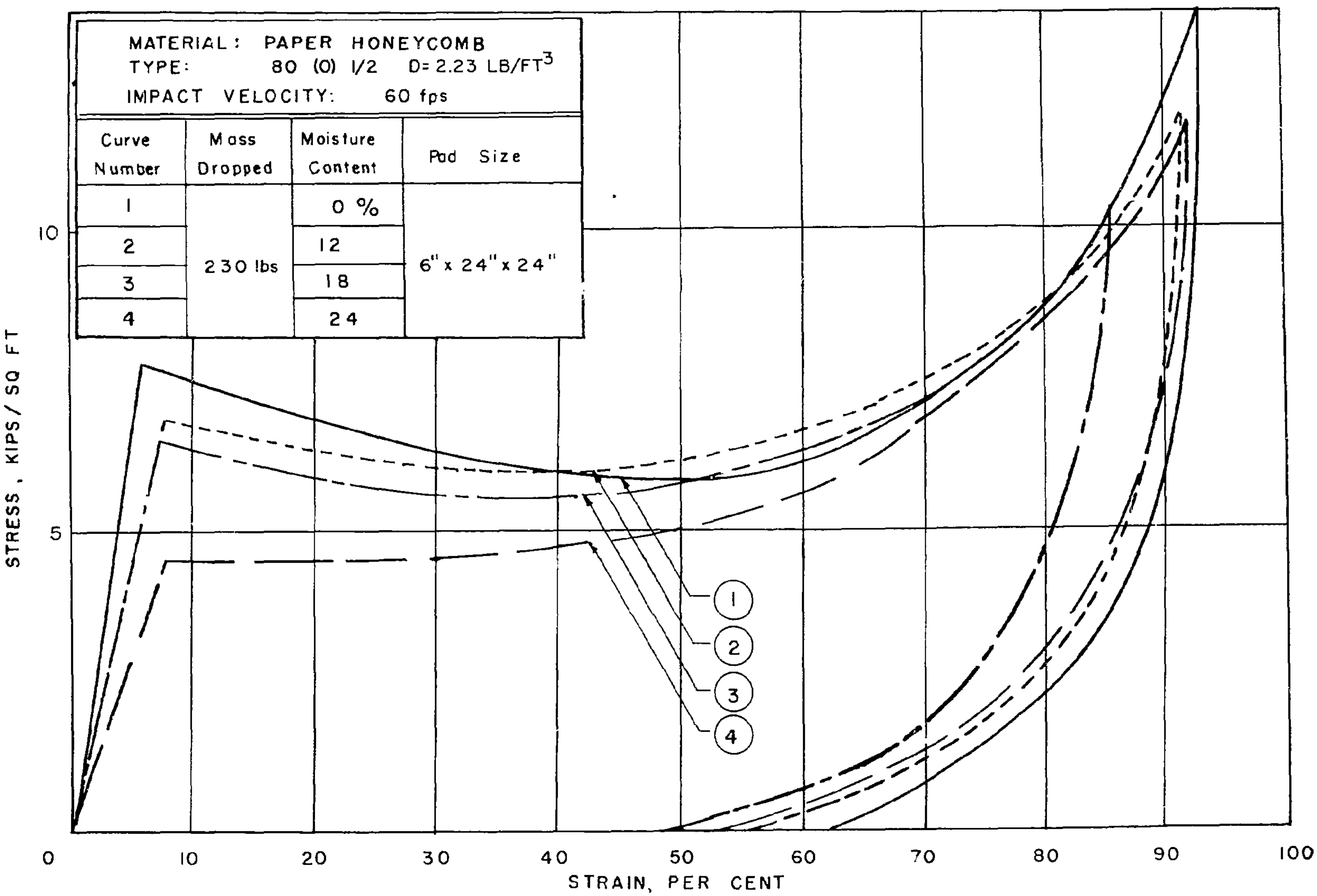


Fig. 4.7. Stress vs Strain For Paper Honeycomb with Varied Moisture Content

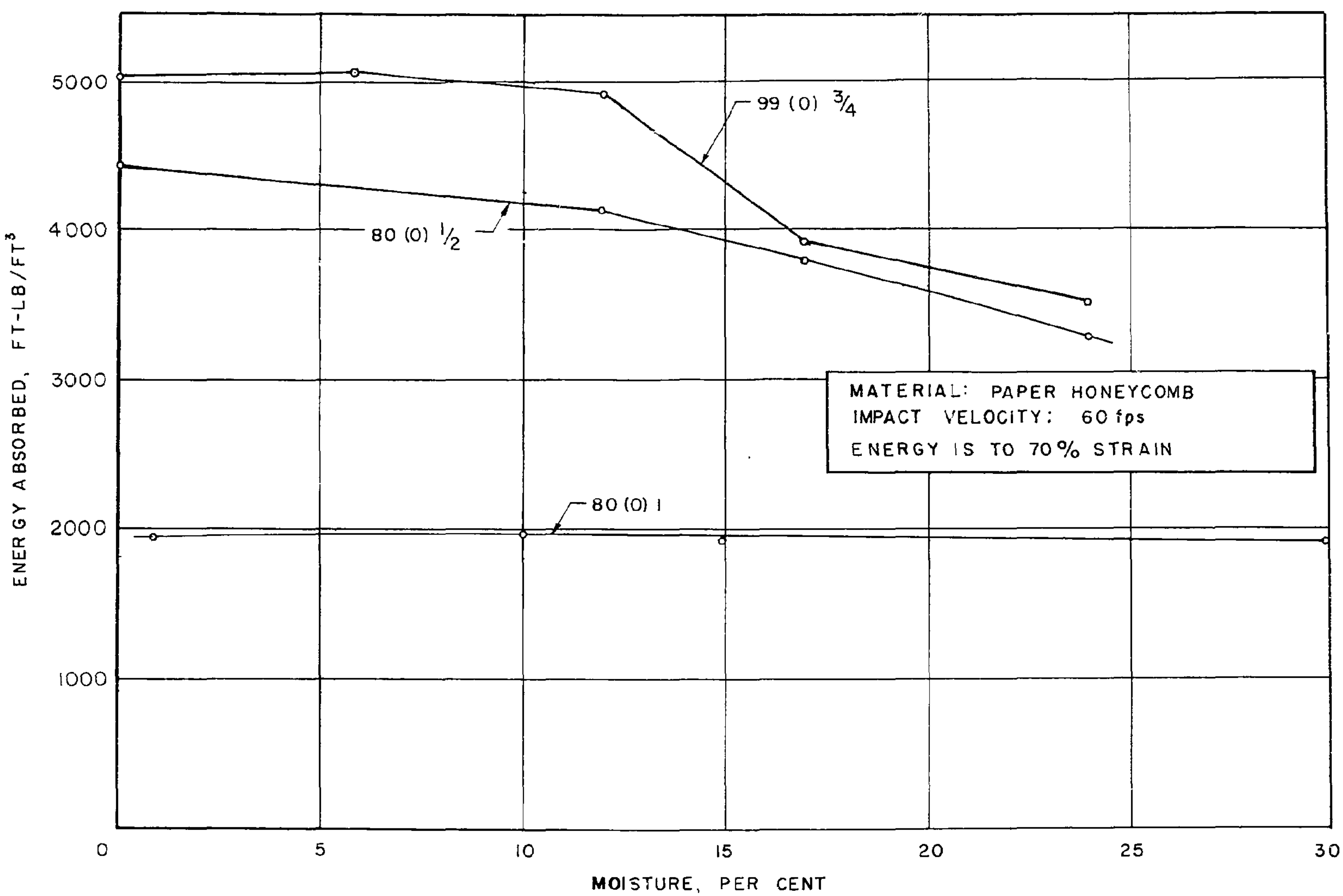


Fig. 4.8. Energy Absorbed vs Moisture Content for Paper Honeycomb at 60 fps Impact Velocity.

humidity for 14 days, the moisture content will reach 11 per cent. Obviously, the size of the pad and the conditions of exposure will both have considerable influence on the moisture absorbed, regardless of ambient conditions. Since the tests made at Forest Products Laboratory were on very small (4 x 4 x 3-in.) samples, large samples might be expected to take a much longer time in absorbing the same percentage of moisture. A series of impact tests was made on 80-0-1/2 paper honeycomb that had been exposed to the weather for 30 days during which time 4.5-in. of rain was recorded. The samples were completely dried by three days' exposure to the sun before the tests were made. No change in the crushing strength could be detected.[1]

It would appear, then, that if reasonable precautions were taken to protect the honeycomb from exposure to extremely humid conditions, the moisture content would present no major problems.

Effects of impact velocity.[4] Figure 4.9 shows the stress-strain curves for 80-0-1/2 paper honeycomb with impact velocities ranging from 30 ft/sec to approximately 90 ft/sec. Inspection of the curves reveals that the cushioning characteristics are not affected appreciably by impact velocity. Minor variations in stress levels do occur, but there is little change in the energy absorption to 70 per cent strain as the impact velocity increases.

The same characteristics hold for other grades of honeycomb as indicated by Fig. 4.10. It may then be concluded from these results, that the energy absorbed to 70 per cent strain is not appreciably affected as the impact velocity ranges from 30 fps to 90 fps.

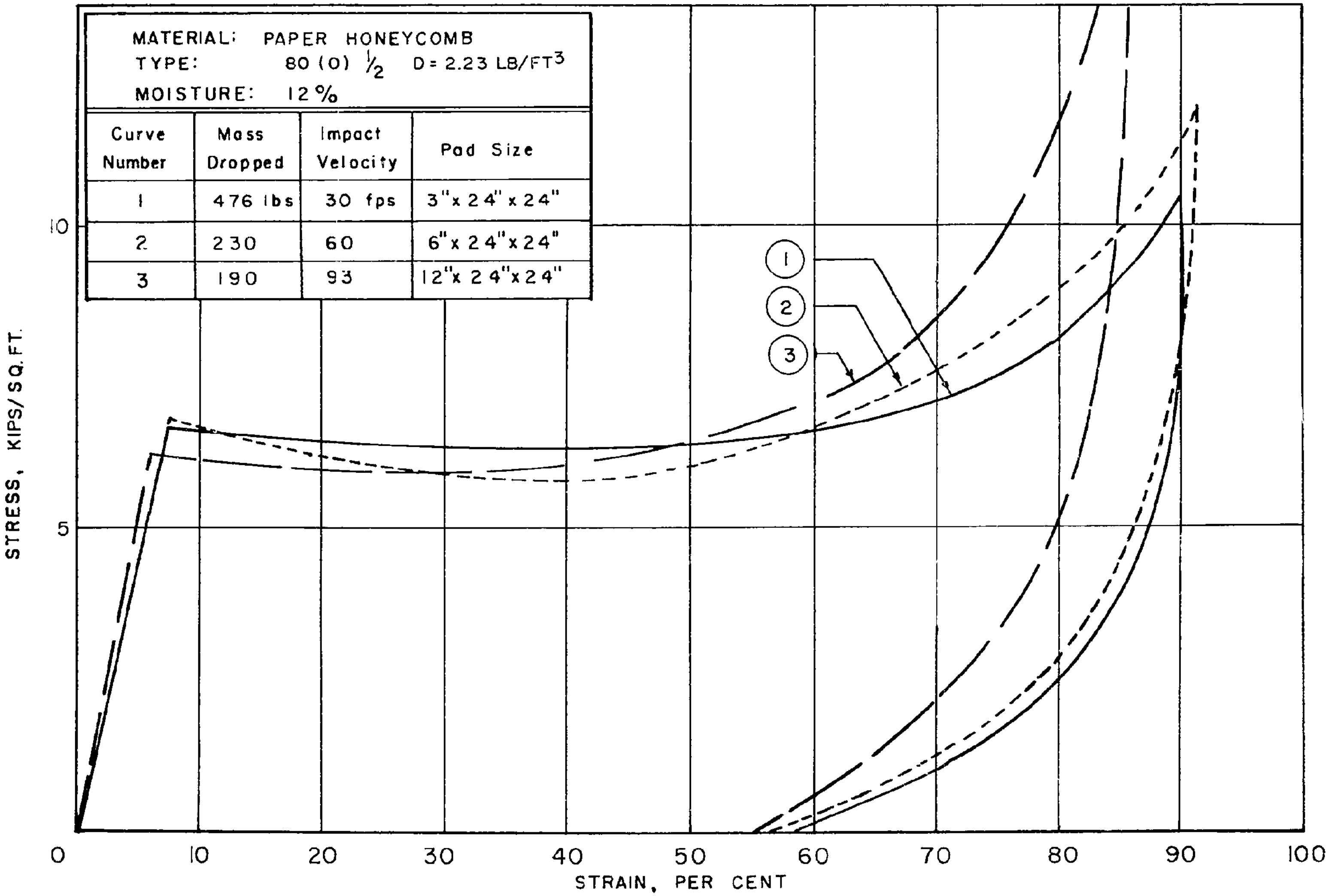


Fig. 4.9. Stress vs Strain for Paper Honeycomb with 12 Per Cent Moisture and Velocity Varied.

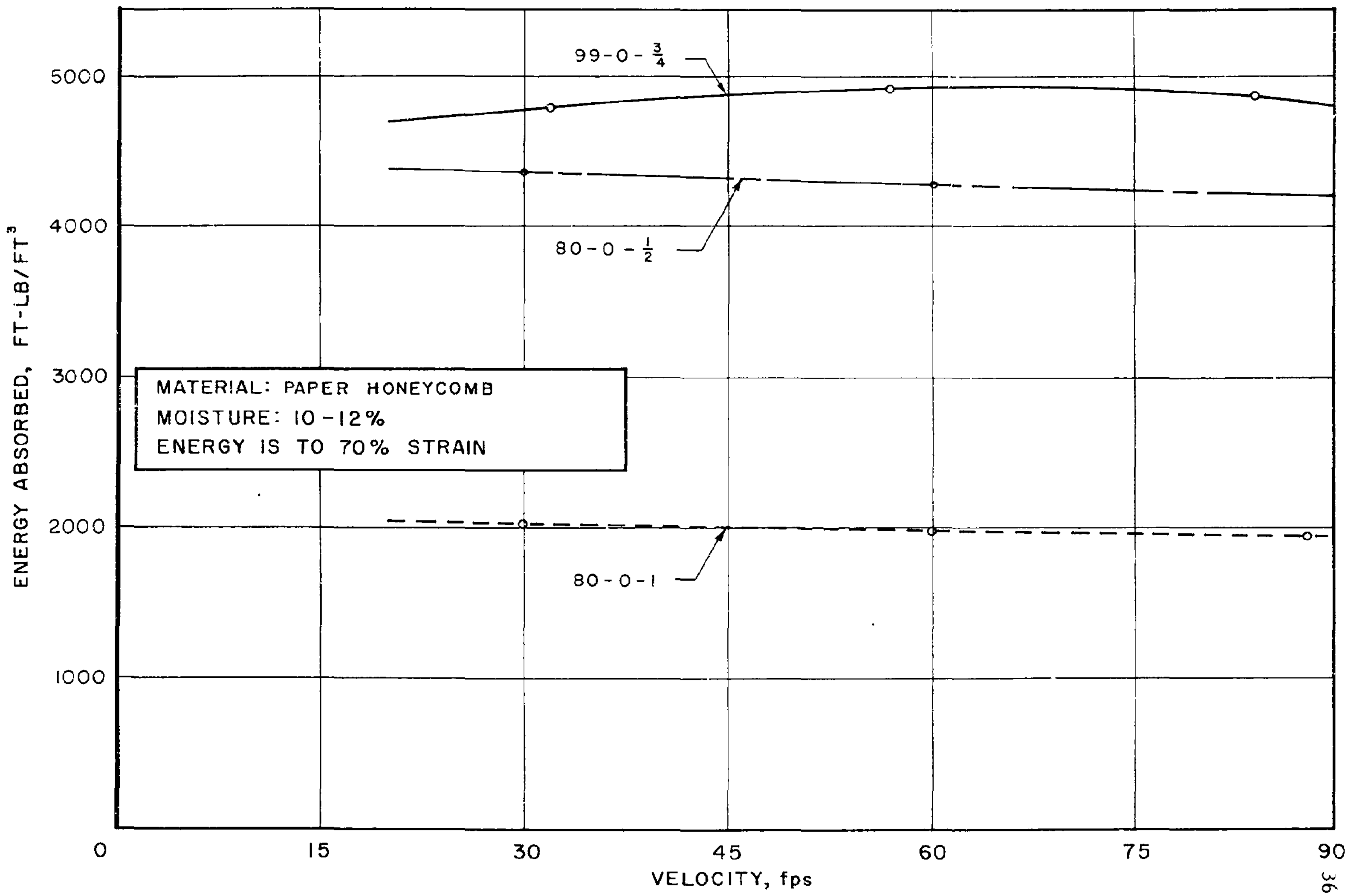


Fig. 4.10. Energy Absorbed vs Impact Velocity for Paper Honeycomb With 10-12 Per Cent Moisture

This is a very significant result since the impact velocity of a vehicle dropping by parachute is difficult to control. If the crushing characteristics did change appreciably with impact velocity, the design of a cushion system would be very complicated.

Summary.

1. For a given set of test conditions, a unique stress-strain curve for a particular grade of honeycomb exists, and it is that curve obtained when the cushion is completely crushed.

2. The average crushing stress for any particular paper honeycomb cushion can be expected to vary $\pm$ 10 per cent from the mean value of that grade of material.[4]

3. Under dynamic loading, the stress and energy-absorption values are considerably larger than those for static loading. For 80-0-1/2 honeycomb, the difference is nearly 100 per cent of the static values.

4. Approximately constant stress levels, with the exception of an initial peak, may be expected up to 70 per cent strain under both dynamic and static conditions. Above 80 per cent strain, however, a rapid increase in stress occurs.

5. For practical cushion design, no appreciable difference in stress-strain characteristics occurs with a variation of impact velocity from 30 ft/sec to 90 ft/sec.

6. Moisture contents of less than 10 to 12 per cent do not modify the dynamic cushioning characteristics of paper honeycomb appreciably.

7. The dynamic stress and energy-dissipation values increase rapidly with increase in density of the honeycomb material, in the

range of materials tested.

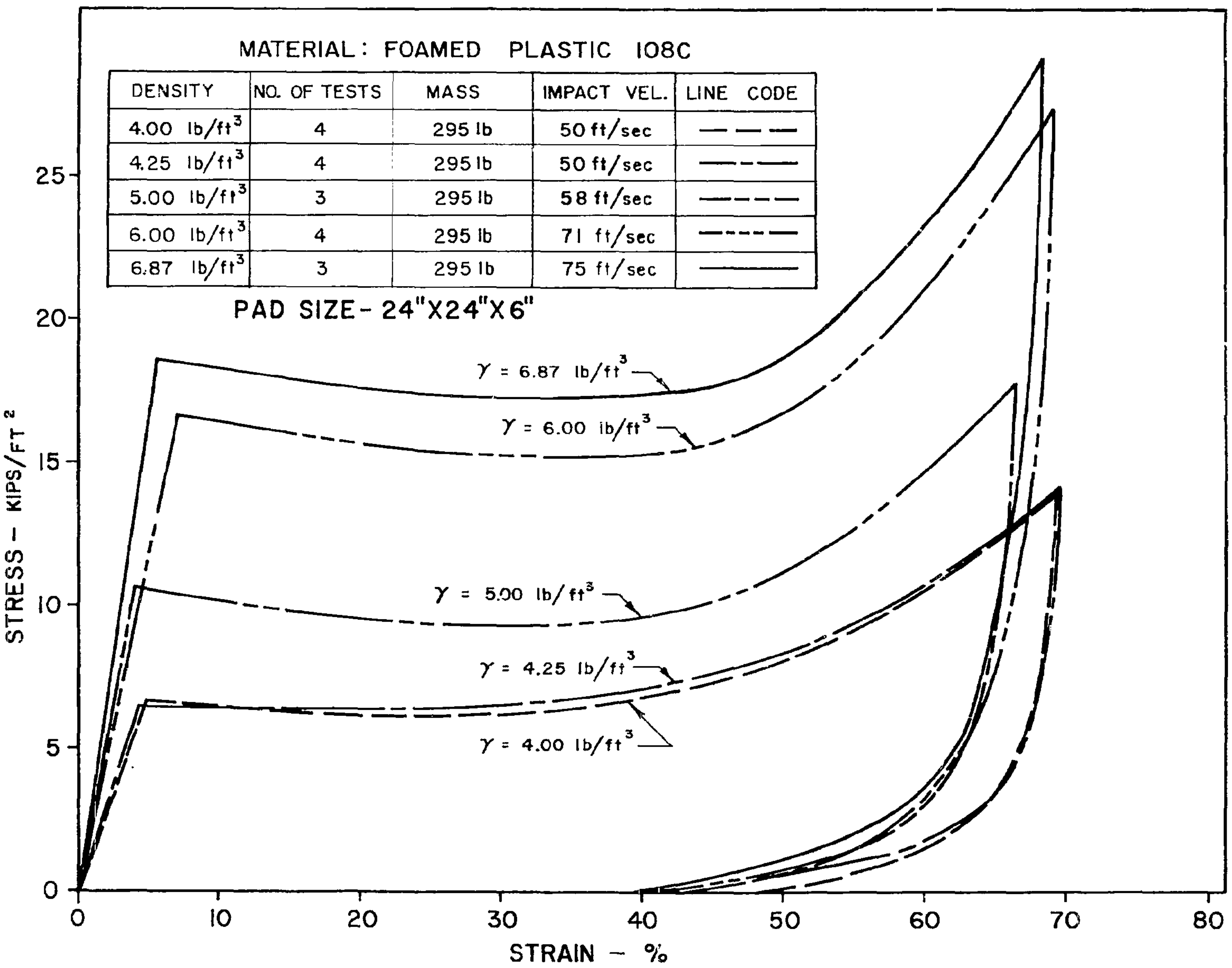
8. The cost per ft-lb of absorbed energy decreases with increase in density for the materials tested.

4.6 Foamed Plastics[5]

Many foamed plastics have been tested to determine their energy absorption characteristics.[6, 7, 8] A selected few are discussed here. It is not to be assumed that these are the best plastics tested or that they are necessarily representative of foamed plastics in general. The results presented here merely serve as examples and pertain specifically to these plastics only.

The dynamic stress-strain characteristics for a polyurethane foamed plastic, designated as Quartermaster 108C, are shown in Fig. 4.11 for various densities of foam. It is immediately apparent that the general shape of the curves is very similar to that found for paper honeycomb. However, the plastic does not produce a peak "starting" stress as prominent as that encountered with paper honeycomb, but it does begin to bottom at about 50 per cent strain as compared to 70 per cent for honeycomb. This would indicate that the optimum strain for plastics should be somewhat lower than that for honeycomb. The foam does, however, approximate an ideal rectangular stress-strain curve closer than does the paper honeycomb.

One advantage associated with foamed plastics is the possibility of producing them in the field. Lockfoam,[8] trade name for a brittle, foamed, isocyanate-base plastic, can be produced without need of



DENSITY	NO. OF TESTS	MASS	IMPACT VEL.	LINE CODE
4.00 lb/ft^3	4	295 lb	50 ft/sec	
4.25 lb/ft^3	4	295 lb	50 ft/sec	
5.00 lb/ft^3	3	295 lb	58 ft/sec	
6.00 lb/ft^3	4	295 lb	71 ft/sec	
6.87 lb/ft^3	3	295 lb	75 ft/sec	

Fig. 4.11 Effect of Density on the Stress-Strain Curve for Foamed Plastic 108C

laboratory equipment, but unfortunately exhibits undesirable brittle characteristics. When impacted, it literally explodes, throwing pieces of plastic in all directions; many of the ejected pieces show little or no deformation, indicating that the entire cushion is not being utilized to dissipate energy. Field expansion of the foams must be foolproof also. Variation in stress-strain characteristics from one batch to another would make accurate cushion design virtually impossible.

Foamed plastics are, in general, more resistant to environmental conditions than honeycomb. As a rule, they are not flammable and have more resistance to moisture because of their low permeability. Temperature variation, likewise, has little effect, as shown in Fig. 4. 12.

While there are many advantages to using foamed plastic as a cushioning material, paper honeycomb still appears to be the best all-round material. Low optimum strains, which must be used when designing with many plastics, necessitates using more material for dissipating a given amount of energy at a given stress level. Cushioning costs are also somewhat higher than for honeycomb, but improved mixes and large-scale production may change this situation.

4.7 Metal Cylinders[9]

Occasionally, there is a need for a cushioning system which will dissipate the energy associated with a point impact load. Paper honeycomb or foamed plastic probably could not be used to advantage in such a situation. However, when a thin-walled metal tube is subjected to an axial compressive load, the walls of the tubes buckle, Fig. 4. 13,

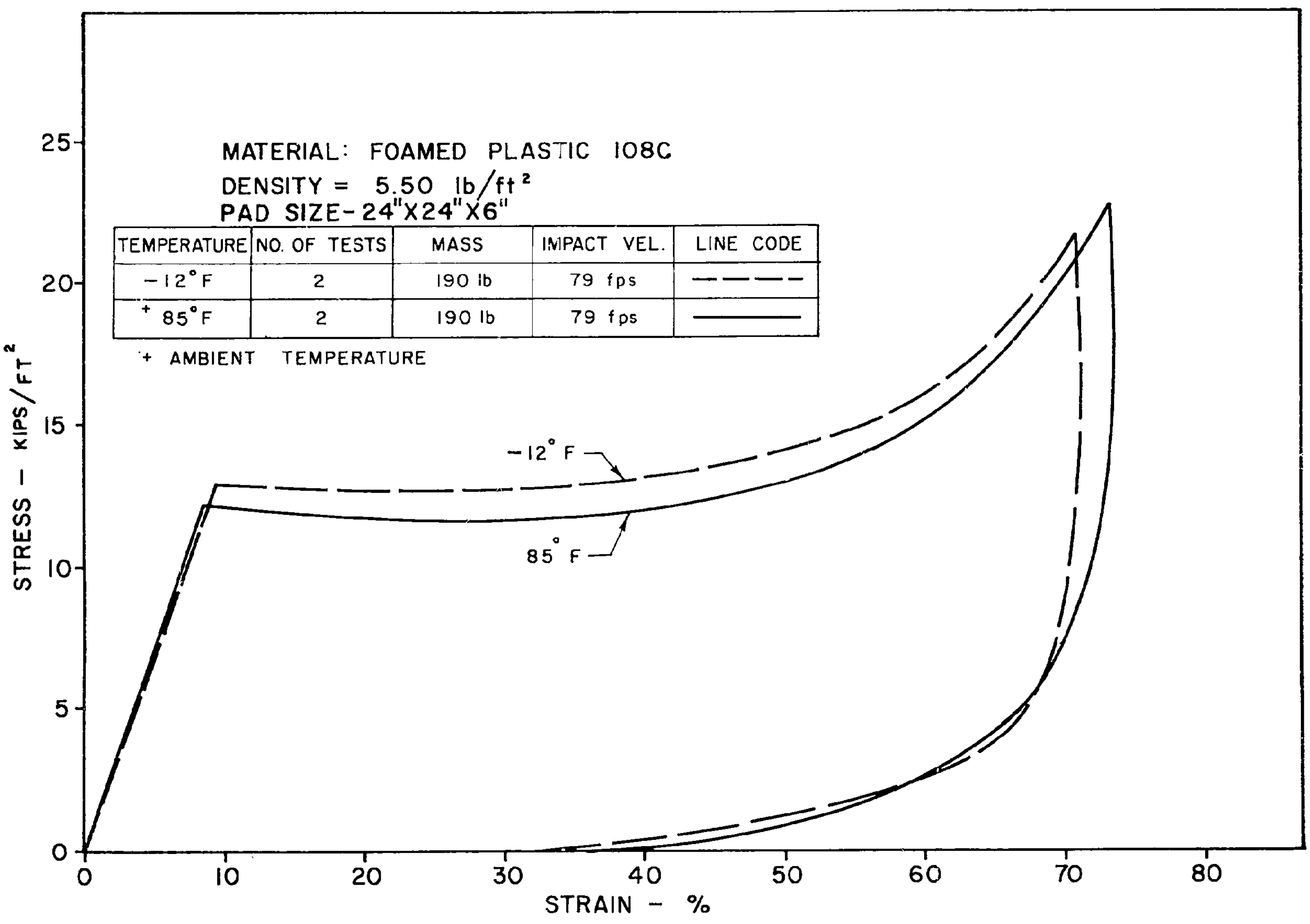


Fig. 4.12 Effect of Temperature on Stress-Strain Curve for Foamed Plastic 108C

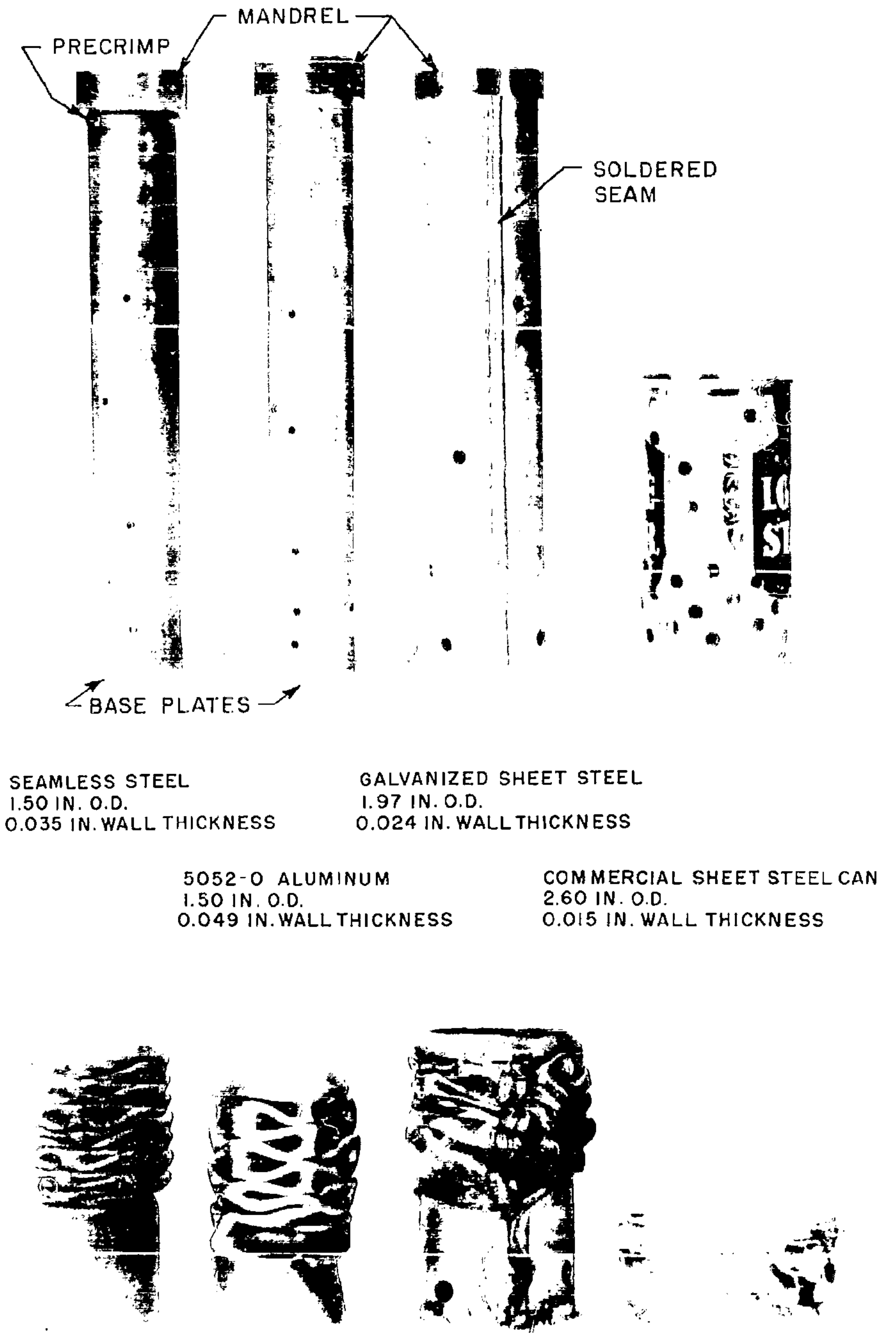


Fig. 4.13. Thin-Walled Tubes Before and After Dynamic Testing.

thereby dissipating the energy of impact. Metal tubes take very little space, and can be used quite successfully with concentrated loads.

Force-strain curves for tubes made of three different materials are shown in Fig. 4.14. Two of the tubes contained fluid which was forced through holes drilled in the sides of the tubes. The kinetic energy imparted to the fluid as it is forced through the holes aids in the energy dissipation.

For a more complete treatment of the use of metal tubes, both empty and fluid-filled, as energy dissipators, reference is made to Cushioning for Air Drop, Part V, Theoretical and Experimental Investigations of Fluid-Filled Metal Cylinders for Use as Energy Absorbers on Impact.[9]

4.8 Aluminum Honeycomb

The dynamic stress-strain curve for aluminum honeycomb is shown in Fig. 4.15.[8] It is similar in shape to the curve for its paper counterpart, but the stresses are larger. When dropping large, heavy pieces of equipment, such as tanks or bulldozers, aluminum honeycomb might be a very satisfactory cushioning agent. The data available on aluminum honeycomb indicates that its cost will limit its use.

4.9 Wood in Lateral Compression[10]

The stress-strain curve for wood in lateral compression indicates that wood is a very good energy absorber. Figure 4.16 shows one method of using this characteristic of wood to good advantage when protecting a

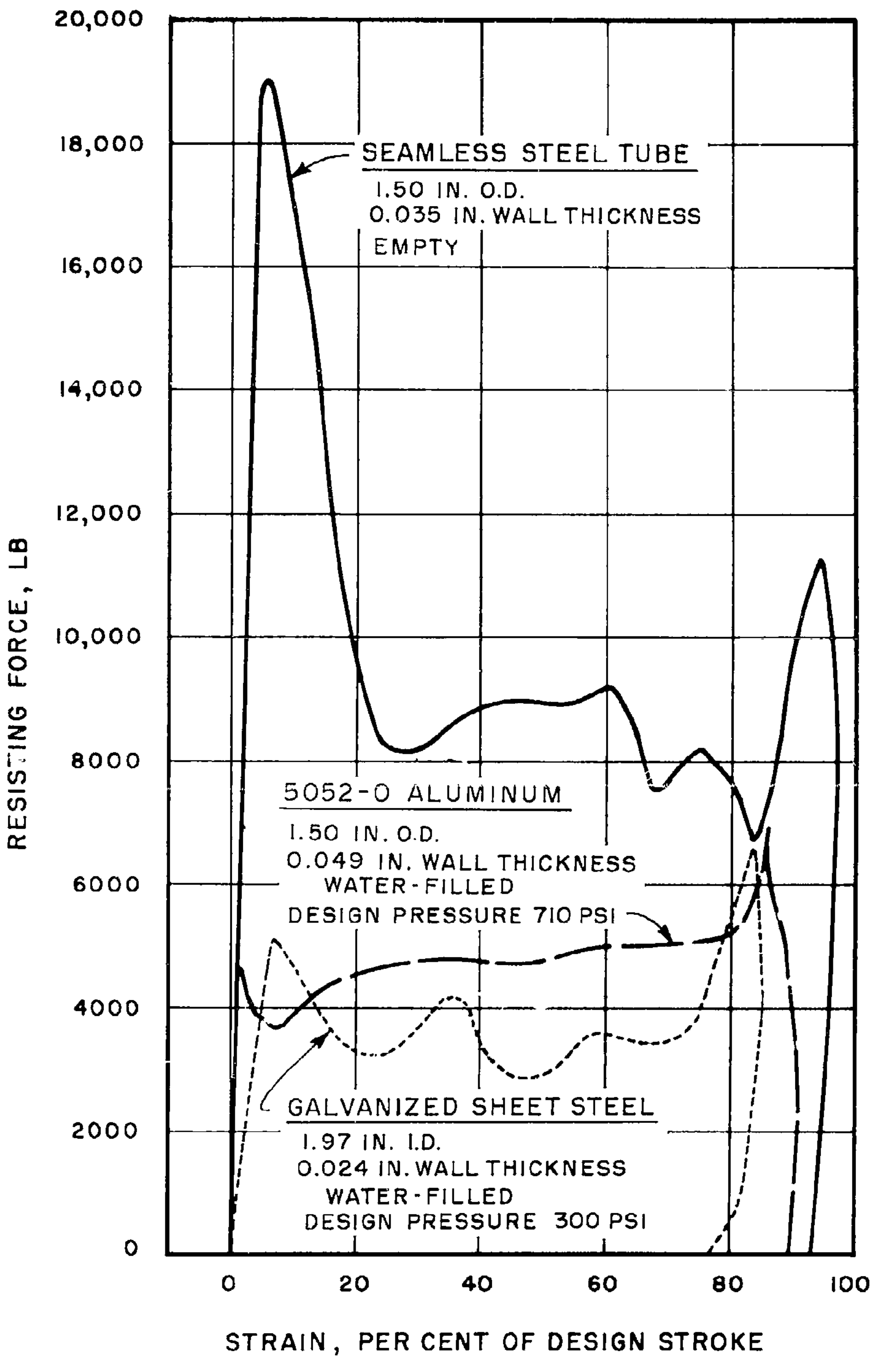


Fig. 4.14 Force-Strain Curves for Dynamic Tests of Steel, Aluminum and Galvanized Sheet Steel Tubes.

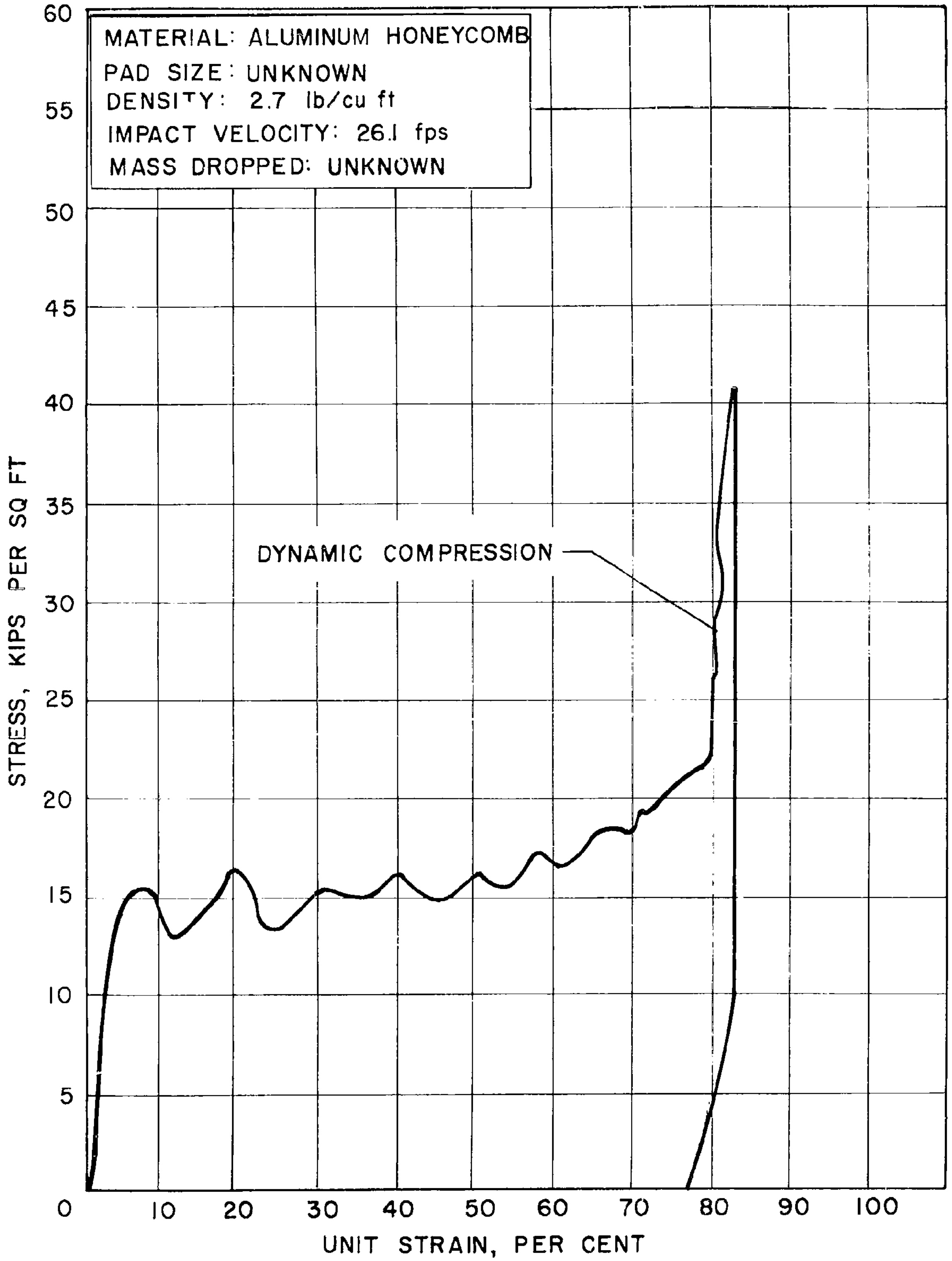
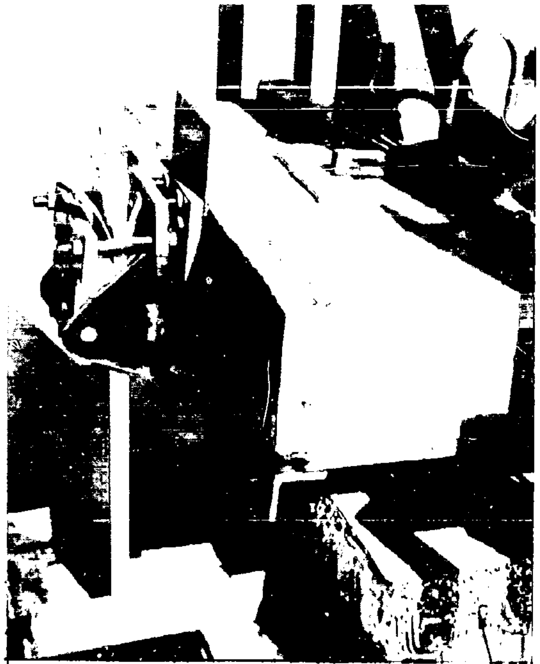


Fig. 4.15. Dynamic Stress-Strain Curve for Aluminum Honeycomb

[FROM SANDIA CORPORATION]

TOP VIEW OF DEVICE, OPENED TO SHOW THE TWO PAIRS OF CYLINDRICAL CRUSHING SURFACES.

DEVICES MOUNTED ON MASS WITH WOOD SPECIMENS IN PLACE BEFORE DROP.



PAPER HONEYCOMB PADS PLACED AS A SAFETY DEVICE IN PRELIMINARY DROPS IN EVENT OF FAILURE OF WOOD.

AFTER DROP

Fig. 4.16. Lateral Compression of Wood

mass from shock loadings. The wood is placed between two cylindrical surfaces which are separated by a distance somewhat less than the thickness of the wood. Upon impact, the wood is forced between the two surfaces and compressed.

The method pictured in Fig. 4.16 is essentially for concentrated forces. It might not be feasible, therefore, to use with some items such as stacks of rations. However, special-purpose application may be made, for example, at load-bearing points on the framework of a vehicle or other piece of equipment.

4.10 Other Materials

Stress-strain curves, both static and dynamic, are presented in Cushioning for Air Drop, Part VIII, Dynamic Stress-Strain Characteristics of Various Materials.[8] For information concerning other cushioning agents, the reader is referred to this publication.

CHAPTER 5

FRAGILITY OF VEHICLES

5.1 Introduction

In order to adequately protect a vehicle from impact, something must be known about its ability to withstand shock loads. The possibility that a vehicle will be damaged by a specific impact loading depends on the characteristics of the impact and of the vehicle. The maximum acceleration, the duration of the impact, the rise time to peak amplitude, the natural frequencies of the vehicle all have some influence on damage susceptibility. No simple, and at the same time reliable, method for characterizing the damage-producing capability of a pulse has been developed to date. An analytical study has shown that the factor AT_d^2 is a very important parameter to consider for fragility studies.[20] Here, A is the maximum acceleration in ft/sec^2, T_d is the pulse length in seconds. The effect of this parameter on the permanent deformation of a structure subjected to a triangular-shaped acceleration pulse is indicated in Fig. 5.1. The results are shown in nondimensional form with ℓ indicating the length of the cantilever beam for which these results were computed, and δ_y, the yield deformation of the beam. This curve indicates that if the acceleration is doubled, and at the same time the pulse duration is decreased by a factor of four, there will be no change in the effect on the structure.

Theoretical studies also show that the effect of the rise time of the pulse on the maximum amplitude is related to the natural period of the system. Generally speaking, the longer the rise time with respect to the natural period of the system, the less will be the effect. If the rise time is about one-quarter of the natural period the maximum amplitude

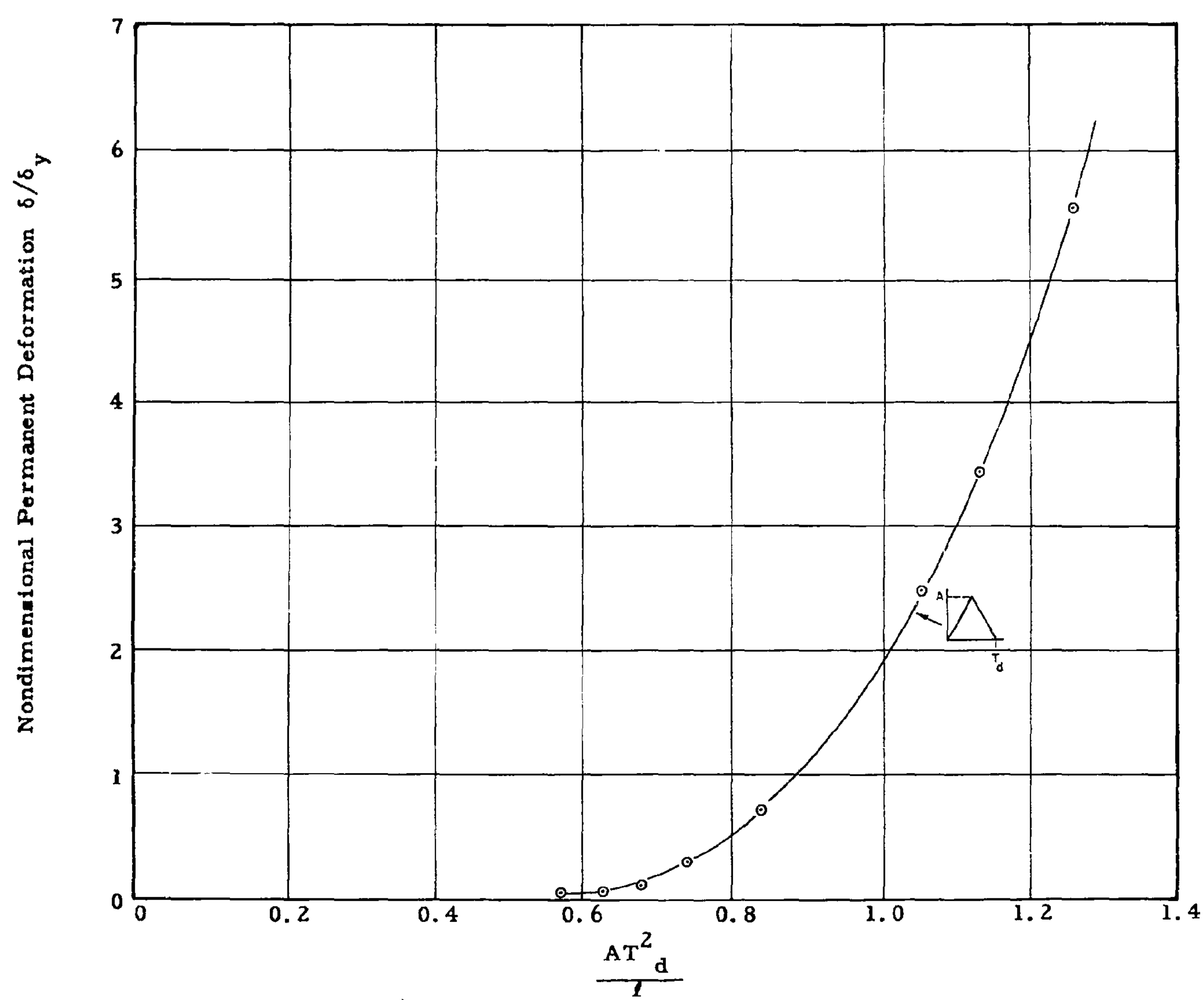


Fig. 5.1. Permanent Deformation Produced by a Triangular Shaped Acceleration Pulse.

is produced.

As a consequence of these complications, the maximum acceleration of the applied pulse expressed in g's is generally used as a convenient design parameter. It must be understood, however, that this is a convenience, and not a scientific verity. As a consequence of this, more "cutting and trying" is necessary in the development of a cushioning system than would be necessary if a better design criterion were available.

It is apparent that damage susceptibility, or fragility, to have any practical significance must be tied as much as possible to a specific method of applying shock. This implies, among other things, a specific cushioning system. To design such a system, requires a knowledge of the factors which contribute to the damage of the vehicle.

Most damage is the result of relative movement between component members of the vehicle. The accelerations resulting from impact cause deformations in all parts of the structure, some of which may be permanent if the relative displacements are large enough. Secondary impact effects caused by two members banging together, can also produce damage. The cushioning system should be designed to reduce relative motion by reducing the amplitude of the acceleration pulse, and by adequately cushioning each section of the vehicle.

Each vehicle, or supply item, will probably have a specific cushioning system designed for it. Since the fragility of an item is dependent to great extent on the method of cushioning, it is probable that a brief testing program will be necessary for each vehicle. However, by knowing the characteristics of the cushioning material, the weight distribution of the vehicle, and the basic concepts behind the fragility rating of a vehicle, a workable cushioning system can be designed with a minimum of testing.

5.2 Vehicle Design Considerations

Damage is often the result of vehicle design rather than cushioning-system design. There are many instances where minor changes in the design of a vehicle could significantly increase its fragility rating and still comply with the dictum, "Ruggedness for air delivery by parachute should not be gained by increasing the weight of the equipment item."[14]

During the design and assembly of a vehicle, consideration should be given to the problems encountered in air delivery of the vehicle. The frame should be strong enough and stiff enough to allow one member to transfer load to another because all frame members will not be supported by cushioning stacks. Lower frame members should be flat bottomed, as wide as possible, and spaced at reasonably close intervals to facilitate the placement of cushioning material and load spreaders. No parts should protrude below the bottom face of the lower frame members because this not only requires that the cushioning system be designed around them, but they are exposed and easily damaged on impact. Fig. 5.2 shows an air line which was placed below a frame member on the water tank trailer, XM107E2, when holes were available for it to go through the member.

Drain plugs on the radiator, gas tank, oil pan, and all grease fittings, should be located in protected positions. Fig. 5.3 shows damage to the gas-tank drain plug of the cargo truck, M37. This damage would have been eliminated had the drain been located on the side of the tank rather than at the rear.

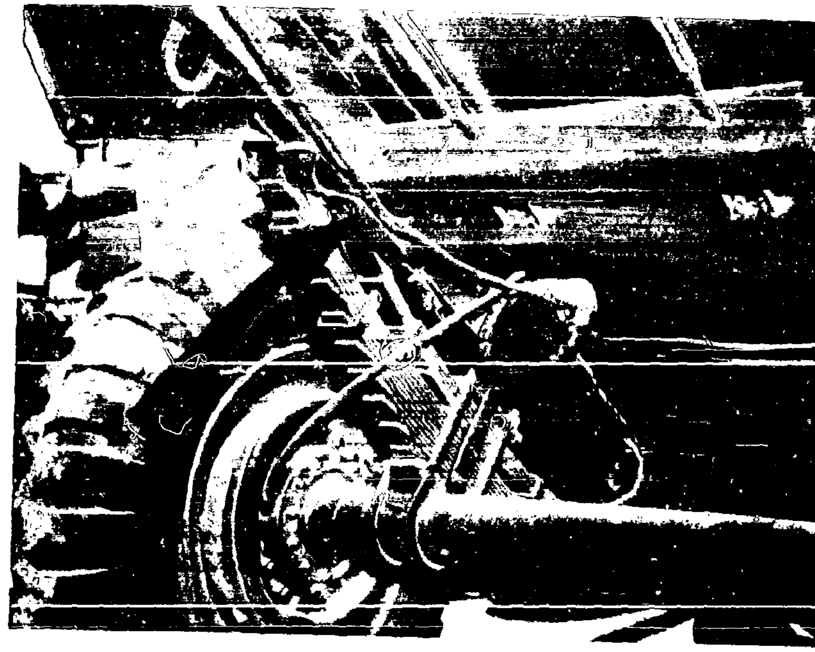


Fig. 5.2 Airline Beneath Frame Member on the Water Tank Trailer, XM107E2

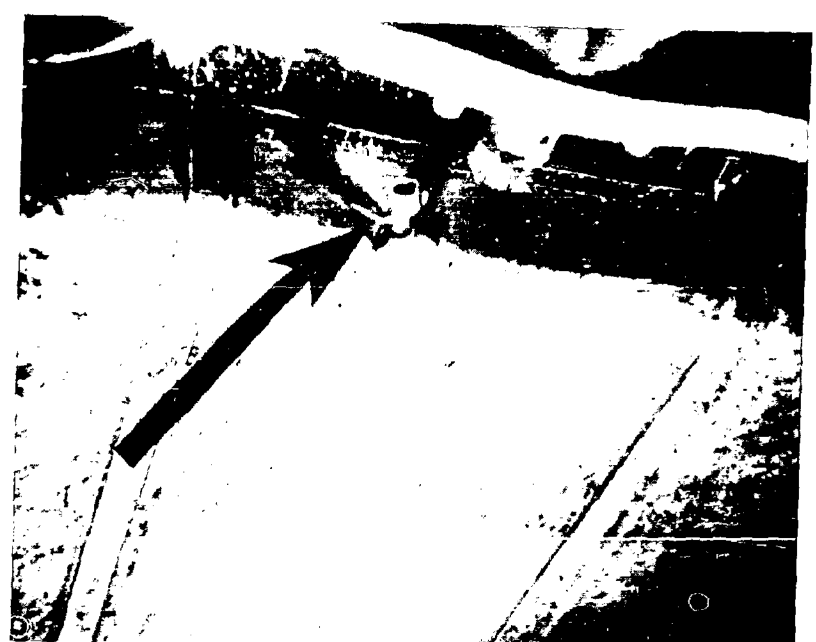


Fig. 5.3 Fuel Tank Drain Plug in Easily Damaged Position at Rear of Fuel Tank on the 3/4-Ton Cargo Truck, M37

When air delivery is considered during the design of a piece of equipment, much time and material can be saved in designing a cushioning system for it. It would also be helpful in the design of the cushioning system to have available detailed weight-distribution charts which locate the centers of gravity of the major components in plan view, and of the vehicle itself.

CHAPTER 6

CUSHIONING SYSTEM DESIGN FOR A HYPOTHETICAL VEHICLE

6.1 Introduction

When the dynamic stress-strain curves for a proposed cushioning material are available, it is a simple matter to design a pad to cushion a particular item using data obtained directly from these curves. It is necessary, however, to know the package weight, W; the specified maximum allowable acceleration, G; and the impact velocity, v_1, or equivalent drop height, h.

All military vehicles have weight-distribution charts from which preliminary weight-distribution factors can be calculated. Usually, these factors will need to be adjusted in order to get a more realistic weight distribution for impact loads.

The maximum allowable G loading, as indicated in Chapter 5, is merely a convenient, but not necessarily accurate, quantity for introducing the ruggedness, or lack or ruggedness, of the vehicle into the cushioning design. The value used is based somewhat on judgment, previous experience with the vehicle, and the specific cushioning system to be used.

The impact velocity depends on the terminal velocity of the package to be dropped. Since most items will be dropped by parachute, the size of the parachute will determine the impact velocity. An equivalent drop height is that height from which the item must be dropped in free fall to attain the same impact velocity it experiences in a parachute drop.

6.2 Basic Equations

From Chapter 4, it was seen that the impact force was

$$F_m = S_m = W(G_m + 1) \qquad \text{- - - - -} \qquad (3.4)$$

If S_a is the average dynamic crushing stress of the cushion material to be used, then the required area will be

$$A = \frac{W}{S_a}(G + 1) \qquad \text{- - - - -} \qquad (6.1)$$

Notice that if the area is increased, the "G-loading" on the vehicle increases also. This contradicts the popular notion that if a little cushioning is good, a lot should be better. Nothing could be more in error, for an excess of cushion area can cause a great deal of damage to the cushioned item.

The required thickness of the cushion will be

$$z = \frac{V}{A} \qquad \text{- - - - -} \qquad (6.2)$$

where z is the required thickness, and V is the required volume. The volume will depend on the amount of energy to be dissipated, which will, in turn, depend on the impact velocity or the drop height.

The potential energy of the package will be

$$U = W(h + \varepsilon z) \qquad \text{- - - - -} \qquad (6.3)$$

where U is the potential energy of the package, h is the drop height, and ε is the design strain.

If the stress-strain curve for the cushion material can be approximated by a rectangle, then the amount of energy per unit volume which

the pad will absorb will be

$$E_n = S_a \varepsilon \qquad ----- \qquad (6.4)$$

The required volume is therefore

$$V = \frac{W(h + \varepsilon z)}{S_a \varepsilon} \qquad ----- \qquad (6.5)$$

and the necessary thickness is

$$z = \frac{W(h + \varepsilon z)}{S_a \varepsilon A} = \frac{W(h + \varepsilon z)S_a}{S_a \varepsilon W(G + 1)}$$

or

$$z = \frac{h}{G\varepsilon} \qquad ----- \qquad (6.6)$$

Since the impact velocity is related to the drop height by

$$v^2 = 2gh \qquad ----- \qquad (6.7)$$

Eq. (6.6) can be represented as

$$z = \frac{v^2}{2gG\varepsilon} \qquad ----- \qquad (6.8)$$

6.3 Considerations

If the cushioning system is to be made from a crushable material such as paper honeycomb, it is likely that the required thickness will not be an integral multiple of the available pad thickness. The cushion should then be built up to the next integral pad thickness to protect against bottoming.

When designing a cushioning system, consideration should be given

to the fact that parts of the vehicle itself will absorb some of the energy of impact. In particular, the tires and springs will deform and absorb energy. Most of this energy will be given back in rebound and consequently it is undesirable for these members to have large deformations. Small deformations, however, can be helpful in absorbing some of the energy of impact, as will be pointed out in the next chapter. Heavy components such as the motor and transmission deserve special consideration also. Movement of these components can produce serious damage to connecting parts such as brackets, gear trains, etc. Care should be taken, therefore, to insure that heavy components and surrounding members move as a single unit. Proper cushion design will effectively eliminate these problems.

CHAPTER 7

CUSHION SYSTEM DESIGN FOR SPECIFIC VEHICLES

7.1 Introduction

Rather than designing for some specific G loading, or for some other characteristic of the shock, the present state of the art indicates that it is best, insofar as a given vehicle is concerned, to design for the minimum acceleration consistent with the properties of the material, stability requirements, the desired impact velocity, mechanical limitations on the arrangement of the cushioning, and the vertical clearance in the aircraft. As indicated in Chapter 6, the volume of cushioning material required for a given vehicle and a given impact velocity is independent of the maximum G loading. Greater stability, and more headroom in the aircraft is gained, however, by designing for the maximum the vehicle can withstand in the way of a shock. In those cases for which a cushioning system, optimized for all other considerations, does not prevent damage to the vehicle, the design of the vehicle should be improved.

Some examples of cushioning configurations, and brief accounts of the development of these configurations, follow. Detailed accounts of the testing program for the development of different cushioning systems will be found in the bibliographic reference to the specific vehicle of interest.

7.2 Cargo Trailer, M101, 3/4-Ton[18]

Cushion system development. Because of its relative simplicity, the 3/4-ton cargo trailer, Fig. 7.1, will be used in the first example of a cushion system design. The final design evolved from a testing program which was more extensive than normally would be required because this was a pilot program. The highlights of the program are presented here.

Preliminary studies were centered about an eight-point support configuration for the cushioning system as shown in Fig. 7.2a and Fig. 7.3. The main disadvantages to this system are its complexity and the resulting tall, slender stacks which tend to be unstable. When supporting such a light vehicle at so many points, the stacks are necessarily slender because of the small area required for each cushion if the G loading of the vehicle is to be kept below a specified maximum.

The next configuration tested was the three-point support shown in Fig. 7.2b and Fig. 7.4. While this configuration was simple and fairly stable, there was a problem of rebound, as shown in Fig. 7.5. This resulted from the fact that the cushioning system dissipated very little of the impact energy, allowing much of it to be absorbed by the vehicle structure and returned as rebound energy.

The cushioning configuration shown in Fig. 7.2c and Fig. 7.6 is the recommended one for the 3/4-ton trailer. It provides a stable, uncomplicated support system that presents no rebound problems. The evolution of this cushioning system, from the other two configurations mentioned, is discussed in detail in Fragility Studies, Part IV.[18]

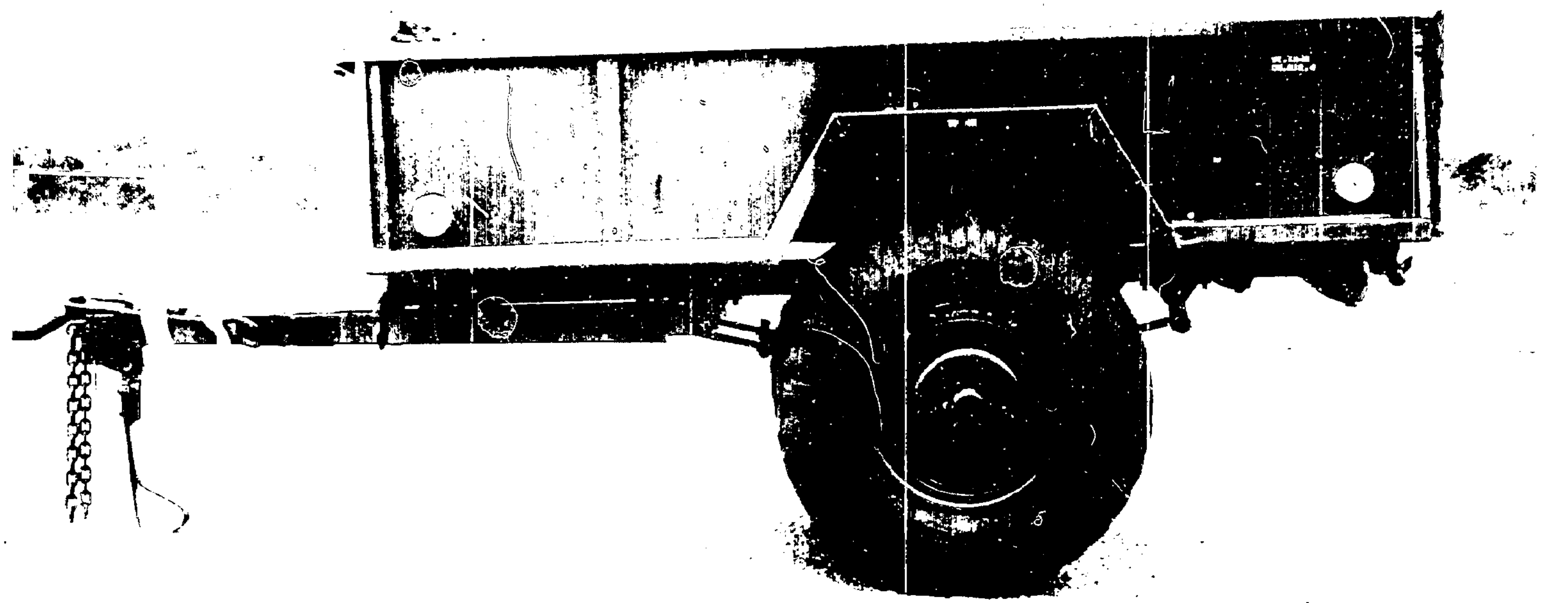
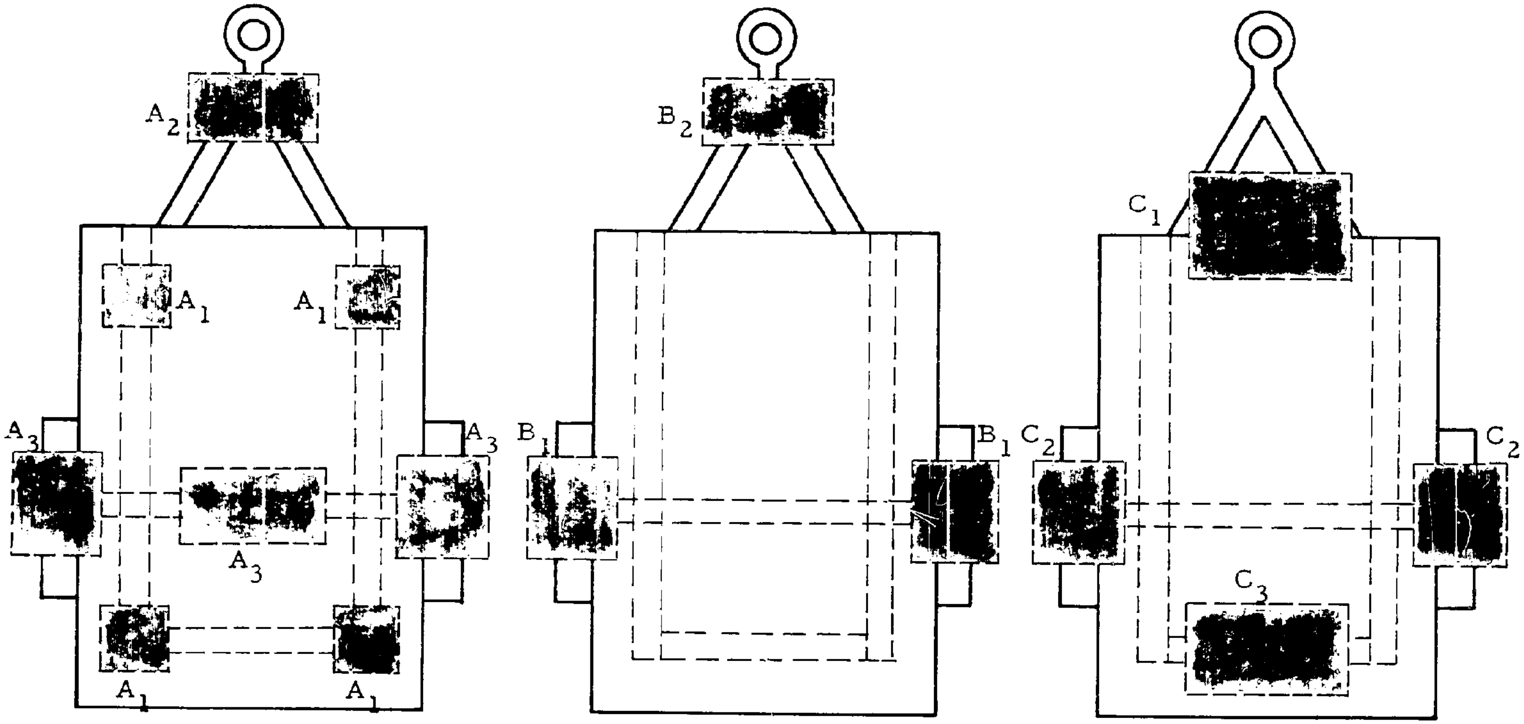


Fig. 7.1. M101 3/4-Ton Cargo Trailer



(a) Eight-Point Support

A_1 - 73 in.^{2}
A_2 - 68 in.^{2}
A_3 - 97 in.^{2}

(b) Three-Point Support

B_1 - 232 in.^{2}
B_2 - 158 in.^{2}

(c) Four-Point Support

C_1 - 213 in.^{2}
C_2 - 145 in.^{2}
C_3 - 145 in.^{2}

Fig. 7.2 Cushioning placement and crushing areas for a theoretical 20g drop for each of the 3 major support configurations investigated.

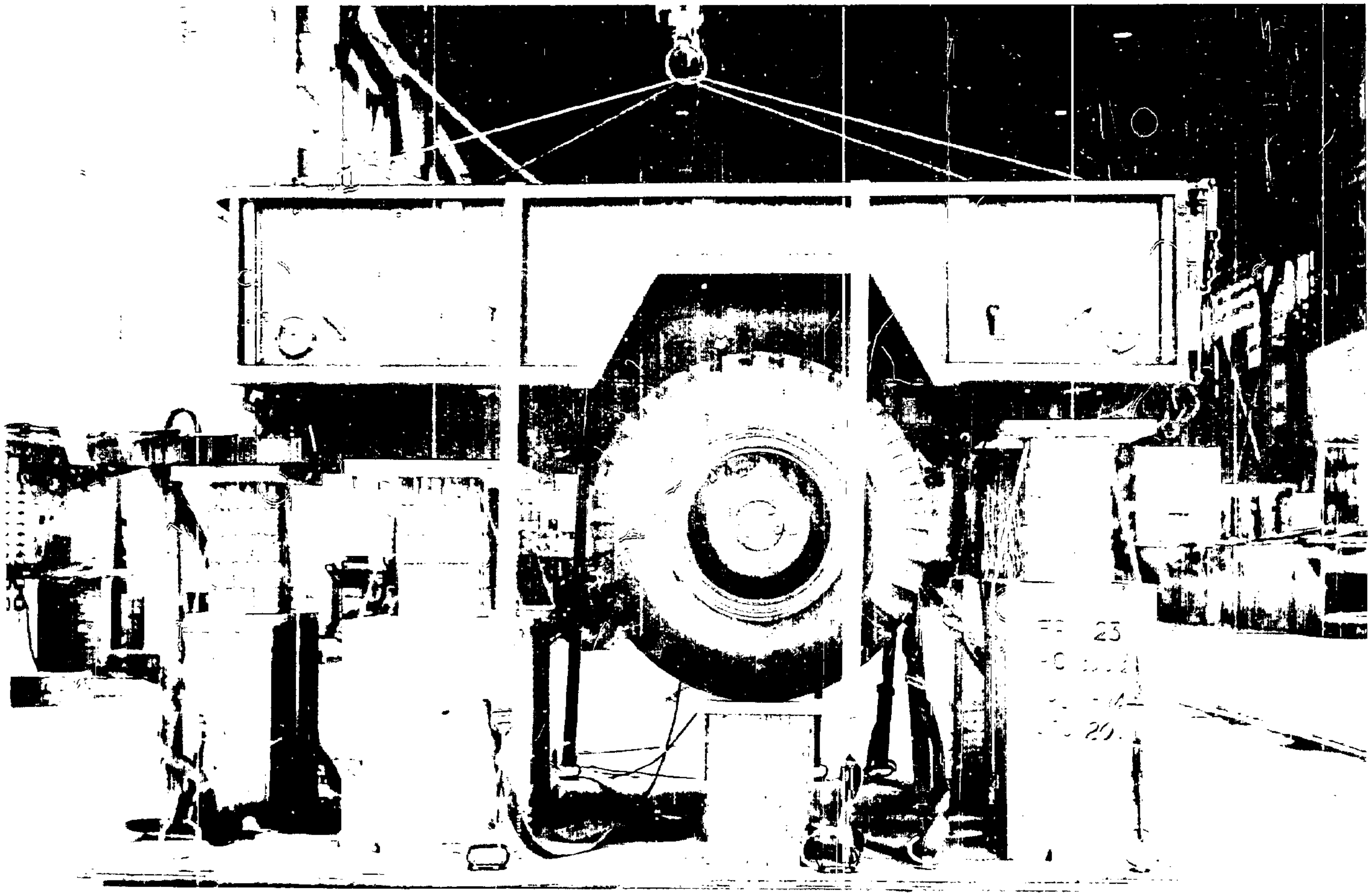


Fig. 7.3. Typical Eight-Point Support Rigging Before Drop

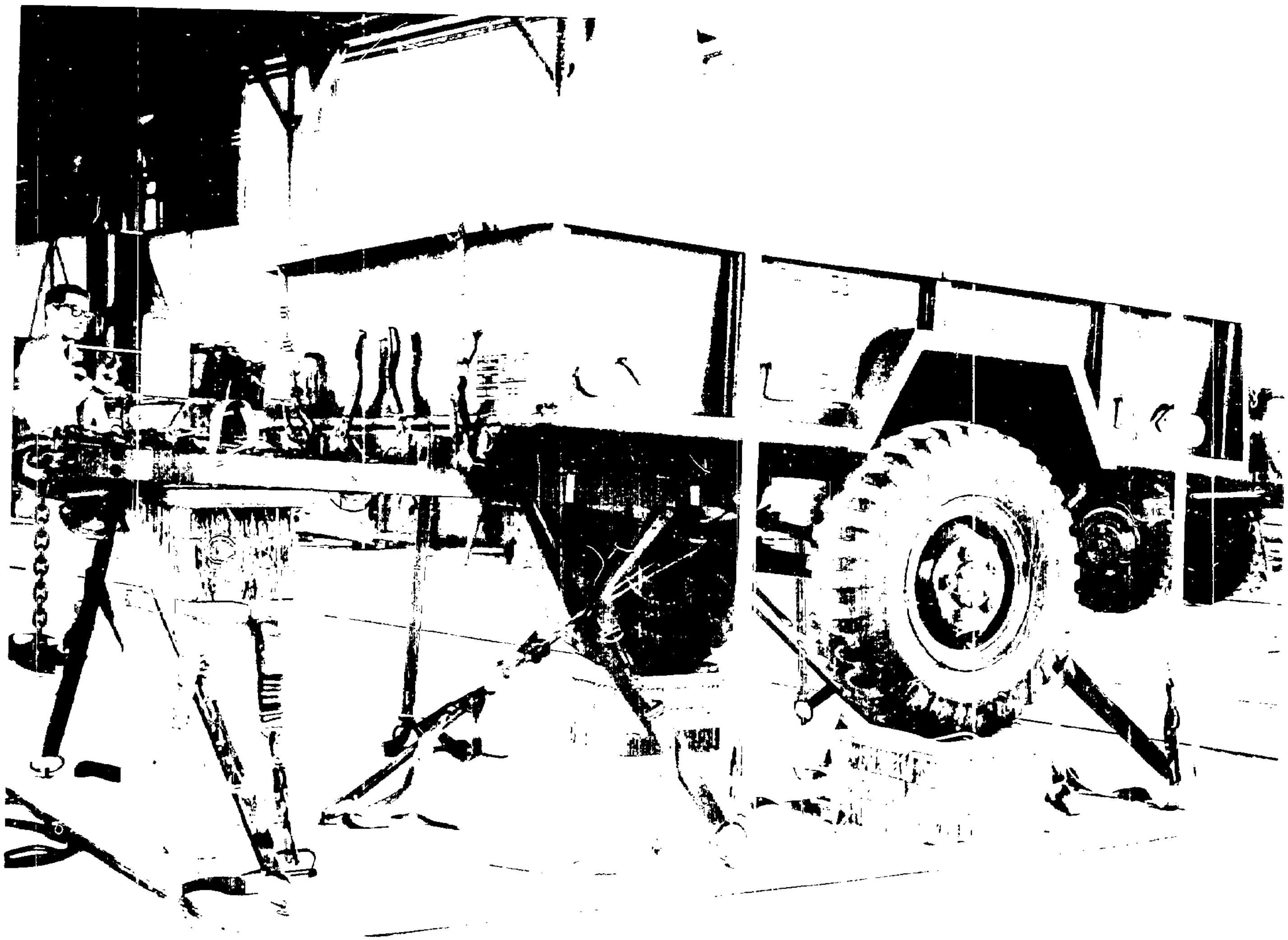


Fig. 7.4. A Typical Before-Drop Rigging with the Three-Point Configuration in Which the Spring Blocks May Be Seen.

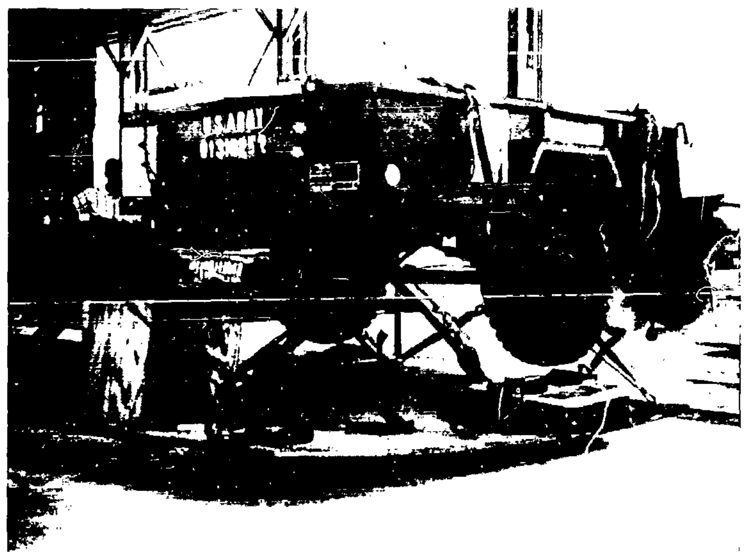


Fig. 7.5. Rebound of 3/4-Ton Trailer After 40g Impact From Height of 14 ft. Note That None of the Stacks of Cushioning Appear to be Completely Crushed.

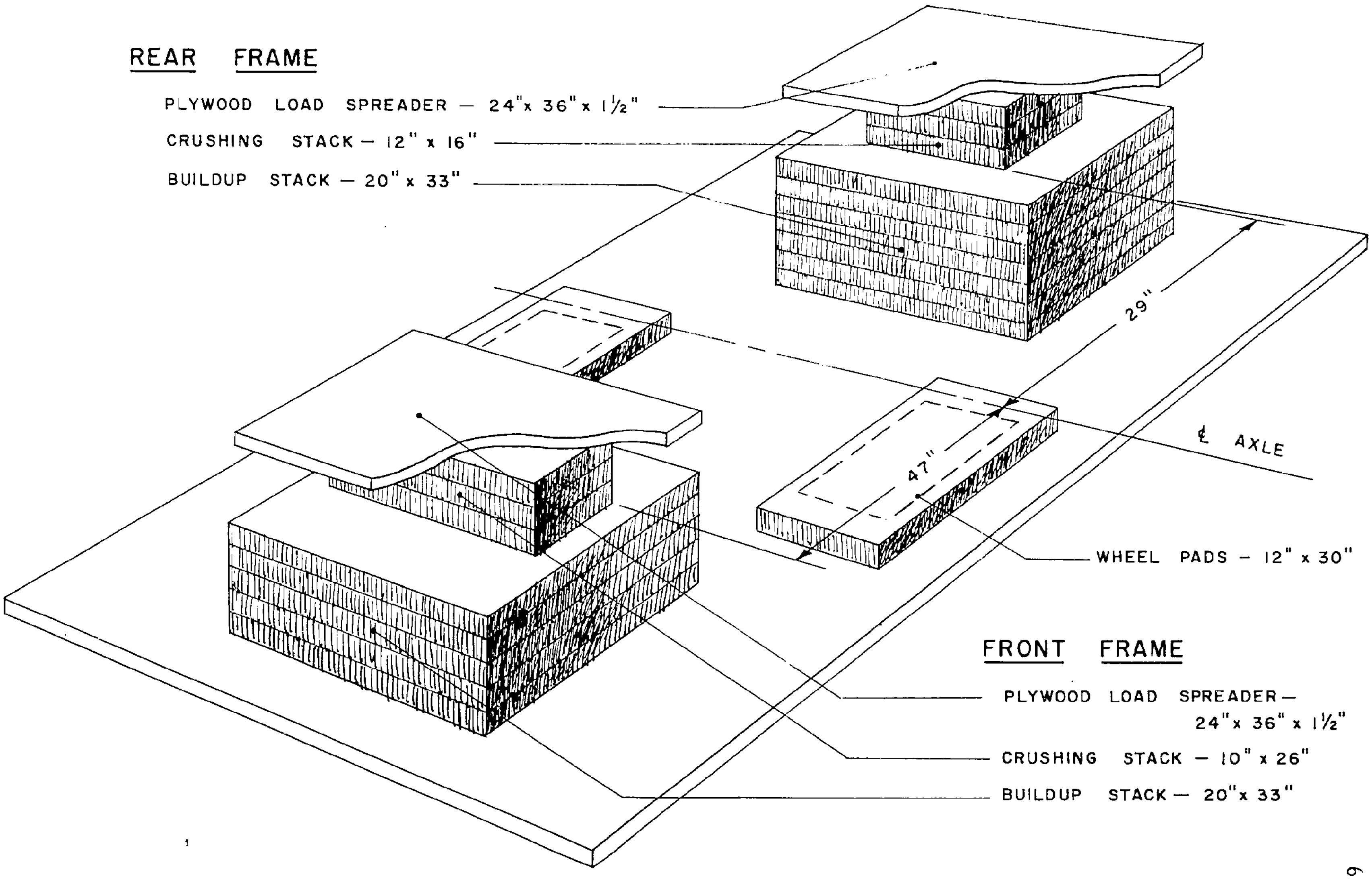


Fig. 7.6. **Recommended cushioning configuration for unloaded 3/4-ton trailer using 80-0-1/2 EDF paper honeycomb.**

Vehicle and cushion characteristics. The cushioning material used for the recommended configuration is 80-0-1/2 EDF paper honeycomb for which the average dynamic crushing stress is 6250 lb/ft^2. For purposes of this example, a design strain of $\varepsilon = 0.70$ will be used and the weight distribution will be taken as 420 lb in front of the axle, 310 lb to the rear of the axle, and 610 lb for the axle and wheels, giving a total of 1340 pounds.

The investigations mentioned in the previous section indicated that it is desirable to allow the tires and springs to absorb some of the energy of impact. The reasoning behind this is that the suspension system of a vehicle is designed to deflect under normal operating loads and that this energy-absorbing capability should be utilized. Doing this allows a minimum cushioning system, height, and this, in turn, increases stability, provided rebound is not excessive. It should be borne in mind, however, that this energy is not dissipated until the vehicle has undergone several cycles of vibration. This vibration is a potential source of damage.

Subsequent calculations will show that, while four pad thicknesses are needed, only one will be used under the wheels. The one pad will be bottomed, but rebound will be slight.

Design calculations. For this problem, a design acceleration of 26g will be used. While this is a somewhat arbitrary figure, it is based on actual test results. At the present time, it appears that this parameter

should perhaps be limited to 20g for most military vehicles. Further experience and further knowledge of the factors which enter the damage-susceptibility relationship may require a revision of this estimate.

The required pad area for the front cushion is

$$A = \frac{W}{S}(G+1)$$

$$A_f = \frac{420}{6250}(26+1) = 1.81 \text{ ft}^2 = 261 \text{ in.}^2 \quad \text{Use 10-in. x 26-in. pad}$$

and for the rear cushion

$$A_r = \frac{310}{6250}(26+1) = 1.34 \text{ ft}^2 = 193 \text{ in.}^2 \quad \text{Use 12-in. x 16-in. pad}$$

The pad under each wheel should have an area of

$$A_w = \frac{305}{6250}(26+1) = 1.32 \text{ ft}^2 = 190 \text{ in.}^2$$

Figure 7.6 shows that pads with much greater areas than that calculated are used under the wheels. However, the required area, 10-in. x 19-in., is cut out but not removed, as indicated by the dotted lines, so that only that portion crushes. The extra pad area around the cutout provides some stability in the event that a horizontal component of velocity is present at impact.

An impact velocity of 30 ft/sec will be used to determine the required pad thickness. This is a reasonable terminal velocity to expect when the trailer is dropped by parachute. An equivalent drop height in free fall is $h = \frac{v^2}{2g} = \frac{30^2}{2(32.2)} = 14$ ft; therefore, the required pad thickness is

$$z = \frac{h}{G\varepsilon}$$

$$z = \frac{14}{(26)(0.7)} = 0.77 \text{ ft} = 9.25 \text{ in.}$$

The calculations require that cushions slightly over three pads thick should be used, necessitating the use of four pads, since 80-0-1/2 EDF paper honeycomb as used by the Army comes only in 3-in. -thick pads. However, actual drop tests indicate that three pads under the frame and one pad under each wheel will adequately cushion the trailer. In most cases, testing will show that less honeycomb thickness can be used than theoretical calculations call for, especially under the wheels as mentioned before, thereby providing a more stable configuration as well as a saving of material. This is because the springs, tires, and other parts of the vehicle absorb some of the impact energy. Actual drop tests and practical experience can be the only guide in reducing the thickness of the pads. When there is doubt, the calculated, or higher, values should be used under all support points.

Load spreaders and build-up stacks. In order to utilize the entire cushion area of the front and rear stacks, load spreaders are used to distribute the load over the pad surface. The large load spreaders, as compared to the smaller crushing stacks, Fig. 7.6, are necessary to distribute the force to the stronger frame members. Build-up stacks of honeycomb are used to raise the crushing pads to contact the trailer frame as shown in Fig. 7.6. The size of these build-up stacks is not critical as long as they are at least as large as the crushing pads and provide a stable support for the vehicle. All pads should be glued together with the load spreader glued on top, and the entire stack glued to the platform. This will prevent

shifting of the stacks during handling before the drop, and provides a more stable cushioning system during impact. The vehicle should be securely tied to the platform. Figs. 7.7 and 7.8 show the trailer with the recommended cushioning system before and after a drop from a height of 14 ft, equivalent to an impact velocity of 30 ft/sec.

The cushion-system configuration presented here provides a drive-on-off capability, so that the trailer can be moved after the drop without having to lift it off the crushed honeycomb pads. This is, of course, an important feature under field conditions.

7.3 Cargo Truck, M37, 3/4-Ton[16]

A more complicated cushion design will be illustrated using the 3/4-ton cargo truck, Fig. 7.9. The recommended support configuration, shown on Fig. 7.10 with an overlay of the truck frame, evolved from a testing procedure which is outlined in detail in the bibliography reference to this section. No major changes in the cushion system design were made during development of the recommended configuration. The first drop was designed for a 10g acceleration and the cushion system supported the vehicle at thirteen points. In order to conserve honeycomb, a drive-on-off capability was not employed, Fig. 7.11. This design was modified to the 10-point support configuration with a design acceleration of 16g which is recommended here. Modifications were made to correct the estimated weight distribution, and to provide a drive-on-off capability.

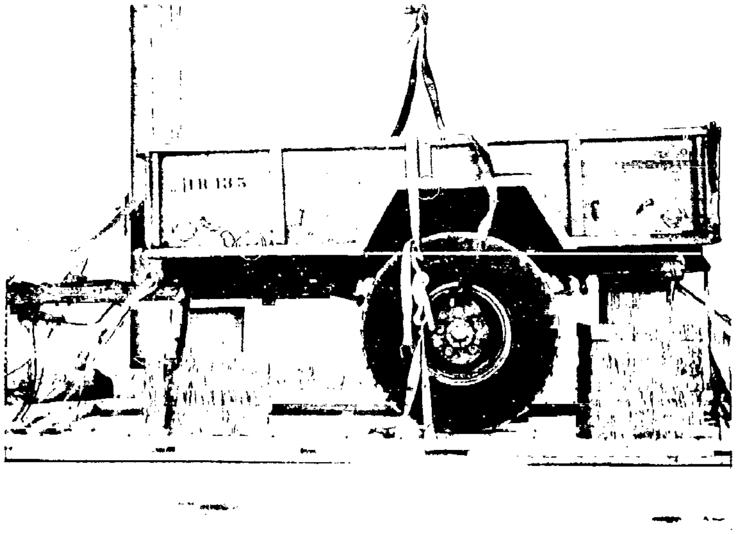


Fig. 7.7. Trailer Rigged for Drop Showing the Configuration Recommended for Dropping the Empty Trailer Using 80-0-1/2 EDF Paper Honeycomb.

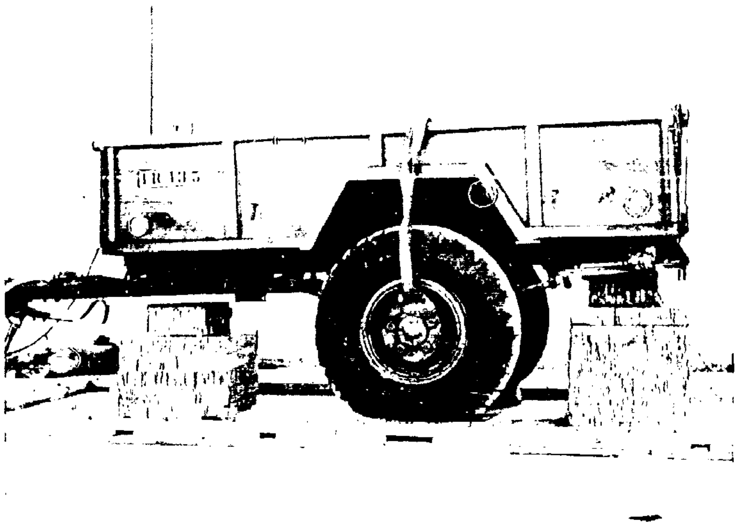


Fig. 7.8. Trailer After Drop.

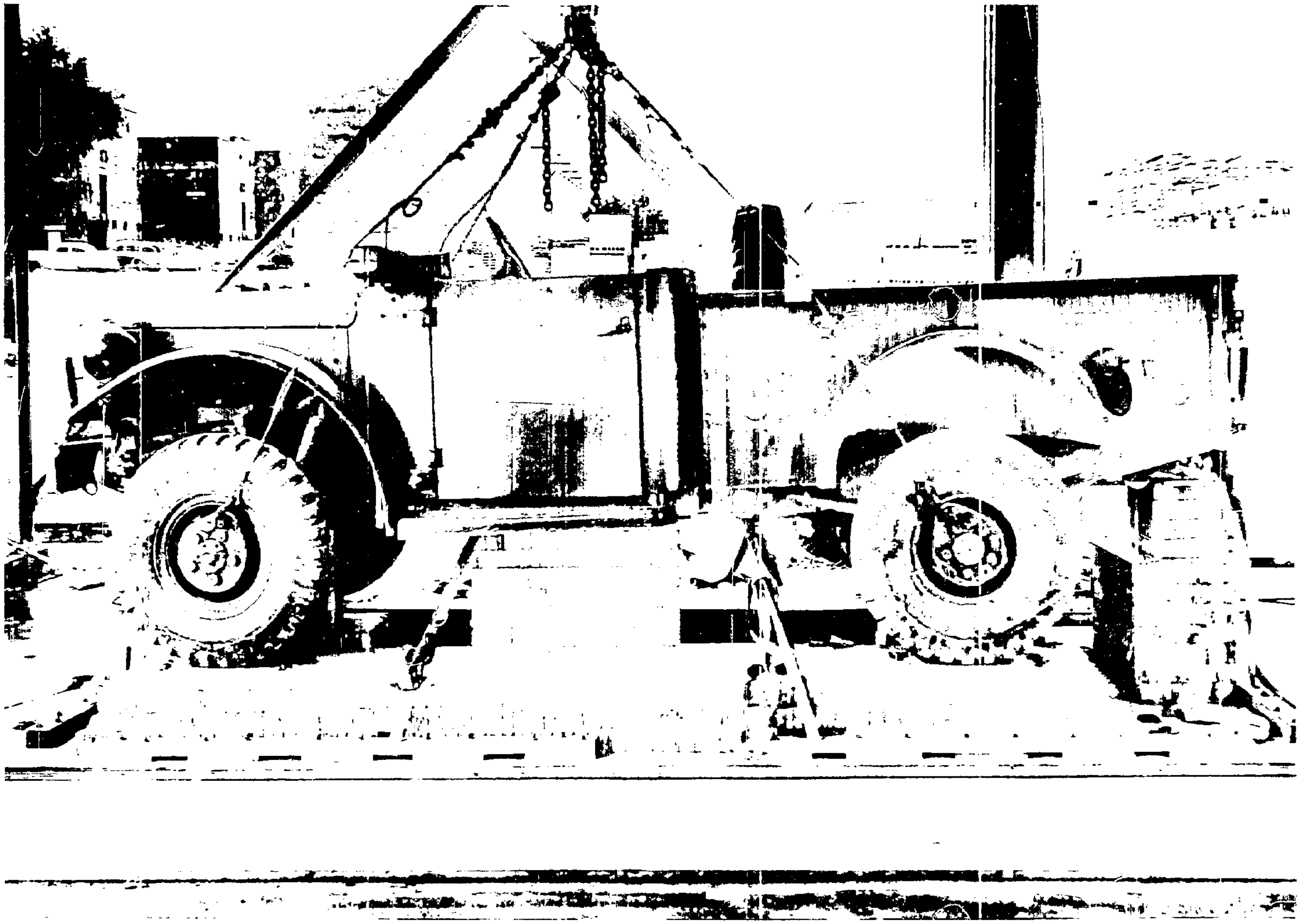
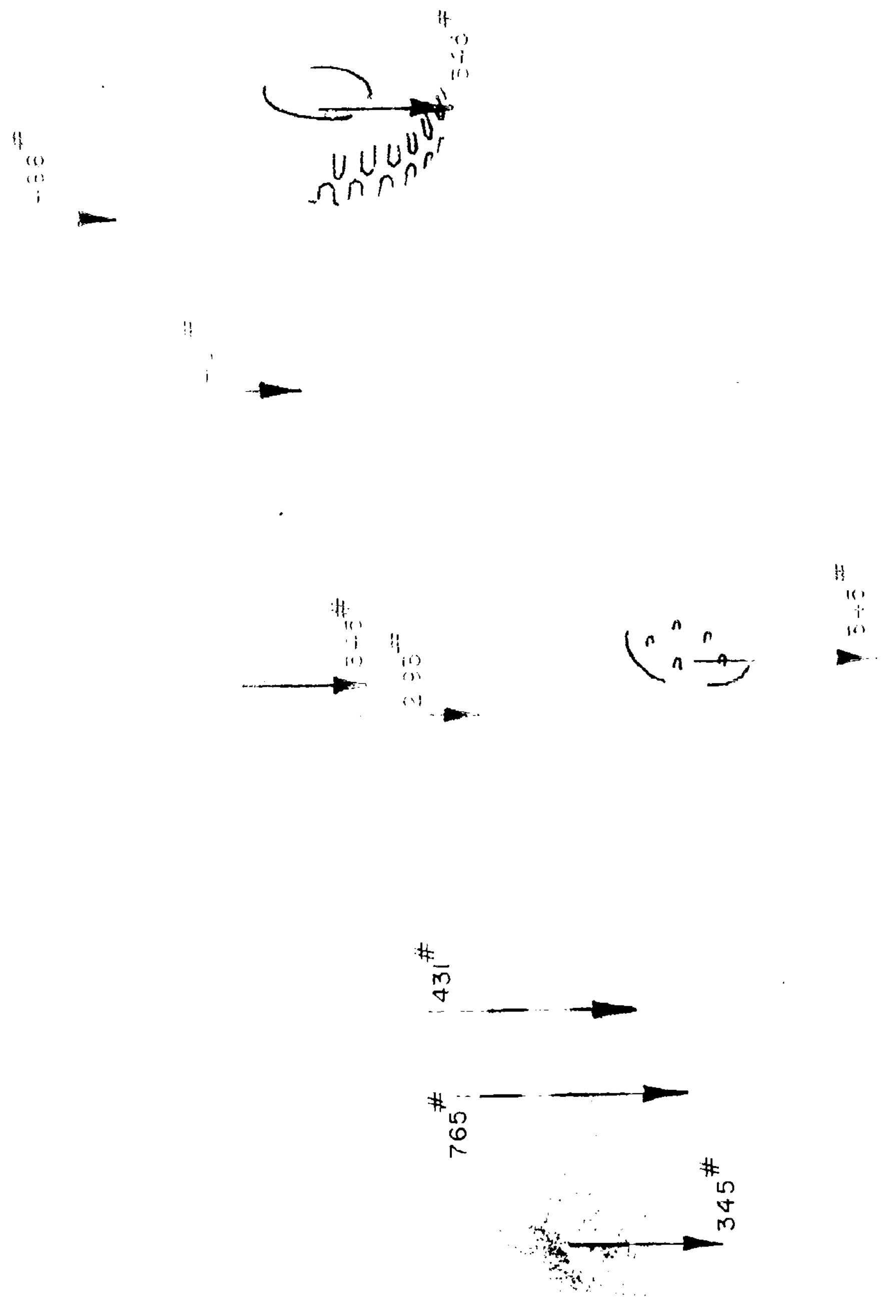


Fig. 7.9 Cargo Truck, M37, 3/4-Ton.



431#
765#
345#

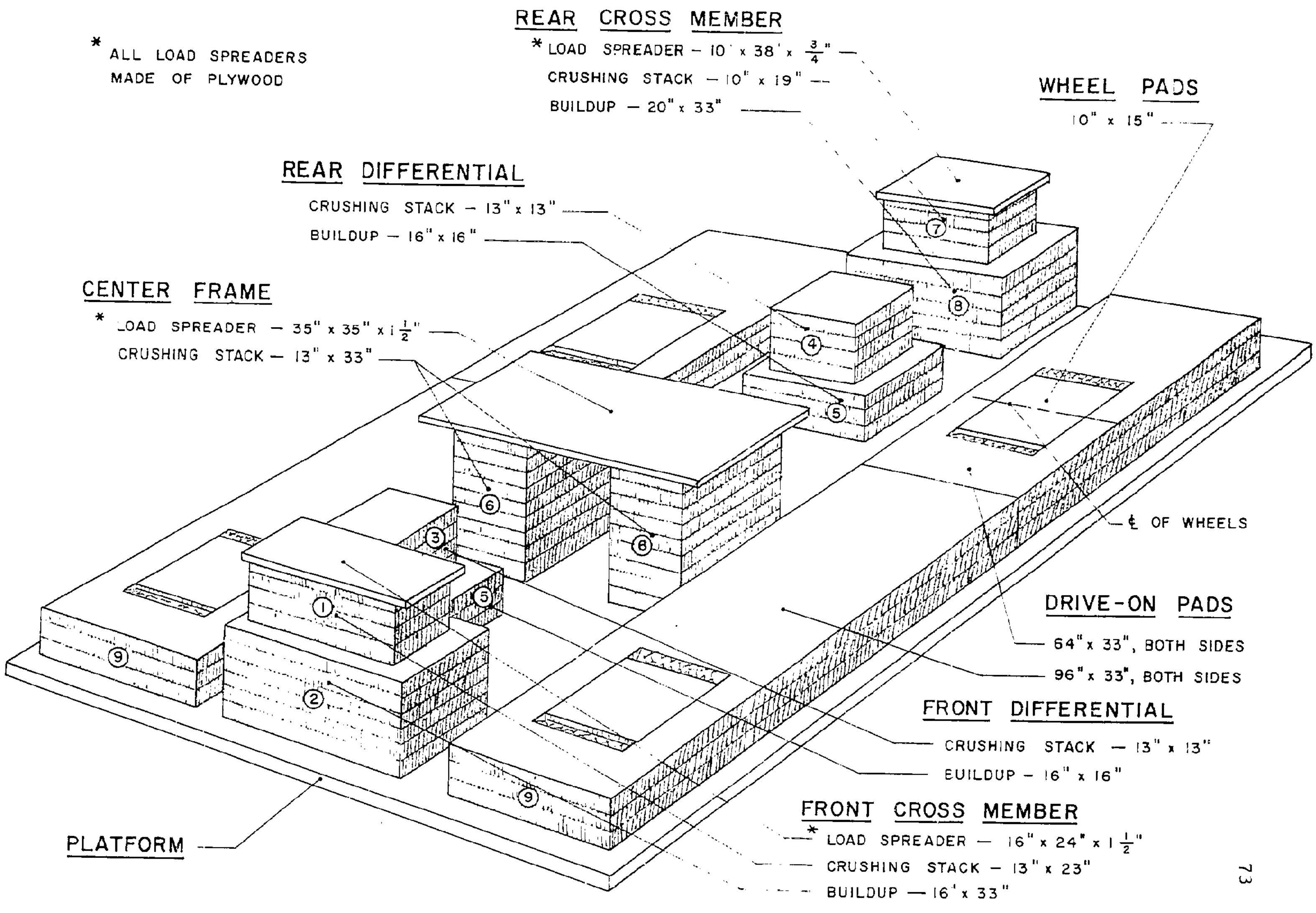


Fig. 7.10 Cushioning Configuration for 3/4 Ton Truck, M37

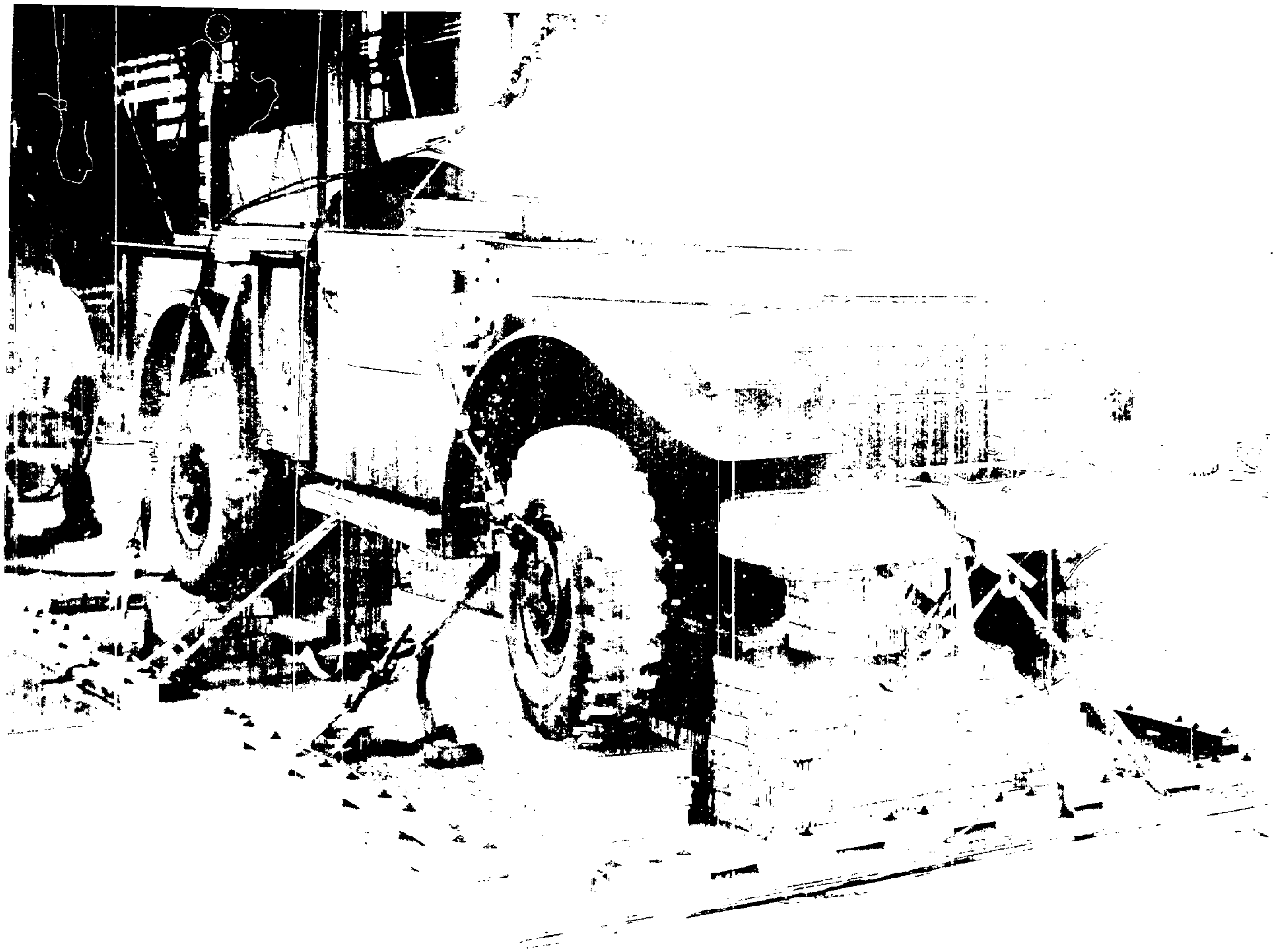


Fig. 7.11. The 3/4-Ton Truck Rigged for First Drop

The cushion configuration recommended here uses three plywood load spreaders and ten crushing stacks of 80-0-1/2 EDF paper honeycomb. Load spreaders are not used under the differentials, cushions 3 and 4, Fig. 7.10, because of the difficulty in fitting load spreaders to the shape of the differential housings, and the fact that most housings make good load spreaders themselves. When it is necessary that the total height of a stack be greater than the required crushing height in order to fit snugly under a member that is to be cushioned, build-up pads are used to increase the height of the stacks.

Design calculations. Weights of the different components, Fig. 7.10, were taken from Ordnance-Corps figures and then adjusted to result in even crushing all around. Figs. 7.12 and 7.13 show the truck in position on the cushion system before and after a 14-ft drop.

Following are the calculations used for designing the cushioning configuration for the 3/4-ton truck, M37. All crushing stacks are the same height except under the wheels. The wheel stacks are reduced one pad thickness for reasons discussed in the section on the 3/4-ton trailer. For the center frame stacks, the build-up stacks were made the same size as the crushing stacks. This provides a stable configuration and at the same time requires less honeycomb. The crushing height was calculated for a design acceleration of 16g, a design strain of 0.70, and a drop height of 14 ft (impact velocity of 30 fps).

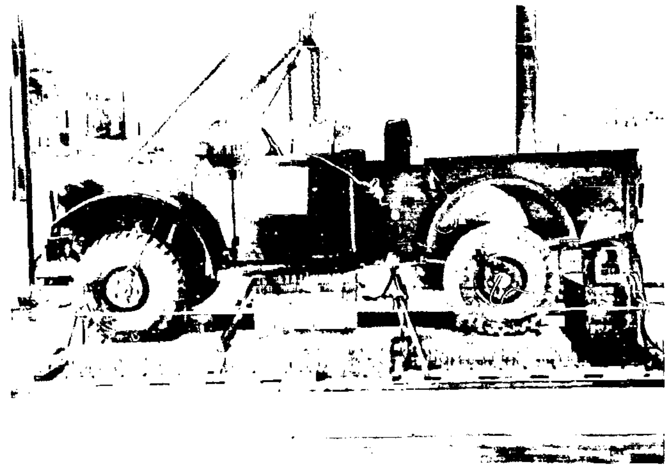


Fig. 7.12. The 3/4-Ton Truck Before Drop.

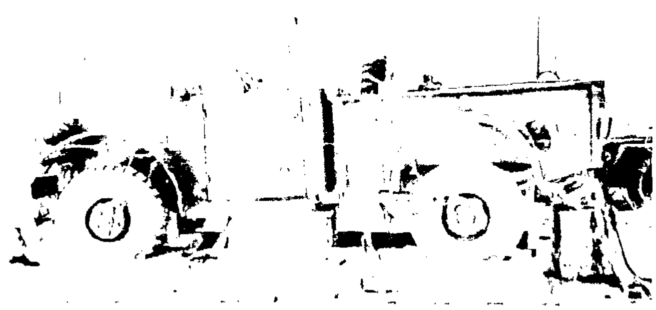


Fig. 7.13. The 3/4-Ton Truck After Drop.

$$z = \frac{h}{G\varepsilon}$$

$$z = \frac{14}{(16)(0.7)} = 1.25 \text{ ft} = 15 \text{ in.}$$

This calculation indicates that five pad thicknesses are needed in each crushing stack. Five pads were used on the preliminary drops, but it became evident that four would be sufficient. Four pads are used under the frame and differential stacks but only three are used under the wheels.

The required areas were calculated as follows:

$$A = \frac{W}{S}(G + 1)$$

Front cross member

$$A = \frac{765}{6250}(16 + 1) = 2.08 \text{ sq ft} = 299 \text{ sq in.,} \quad \text{Use 13-in. x 23 in.}$$

Front differential

$$A = \frac{431}{6250}(16 + 1) = 1.17 \text{ sq ft} = 168 \text{ sq in.,} \quad \text{Use 13 in. x 13 in.}$$

Center frame

$$A = \frac{2193}{6250}(16 + 1) = 5.96 \text{ sq ft} = 858 \text{ sq in.,} \quad \text{Use 2 @ 13 in. x 33 in.}$$

Rear differential

$$A = \frac{431}{6250}(16 + 1) = 1.17 \text{ sq ft} = 168 \text{ sq in.,} \quad \text{Use 13 in. x 13 in.}$$

Rear cross member

$$A = \frac{486}{6250}(16+1) = 1.32 \text{ sq ft} = 190 \text{ sq in.}, \text{ Use 10 in. x 19 in.}$$

Wheels, each

$$A = \frac{345}{6250}(16+1) = 0.94 \text{ sq ft} = 135 \text{ sq in.}, \text{ Cut out 10 in. x 15 in. and precrush around both ends.}$$

Recommended procedure for placing the cushioning. Following are some of the specific techniques employed in placing the cushioning pads for the cargo truck. They serve as examples of the practical considerations which must be taken into account after the theoretical calculations have been made.

1. Place the 12 platform pads on the platform 3 deep with a distance of 33-in. between. Using a keyhole saw, cut 10-in.-wide by 15-in.-long areas through the honeycomb all the way to the platform for the 4 tires to rest on. (See Fig. 7.14)(The wheelbase of the truck is 112 in, and the track is 72 inches) Take precautions that the cut areas are at least 6 in. from the edge of the platform stack to prevent the wheels from crushing through the honeycomb laterally when a horizontal velocity component is encountered.

2. Using some form of ramp up to the height of the 9-in. platform stacks of honeycomb, drive the truck onto the pads, carefully centering all four wheels over their respective cut-out crushing areas on the platform pads. To keep the tires from crushing

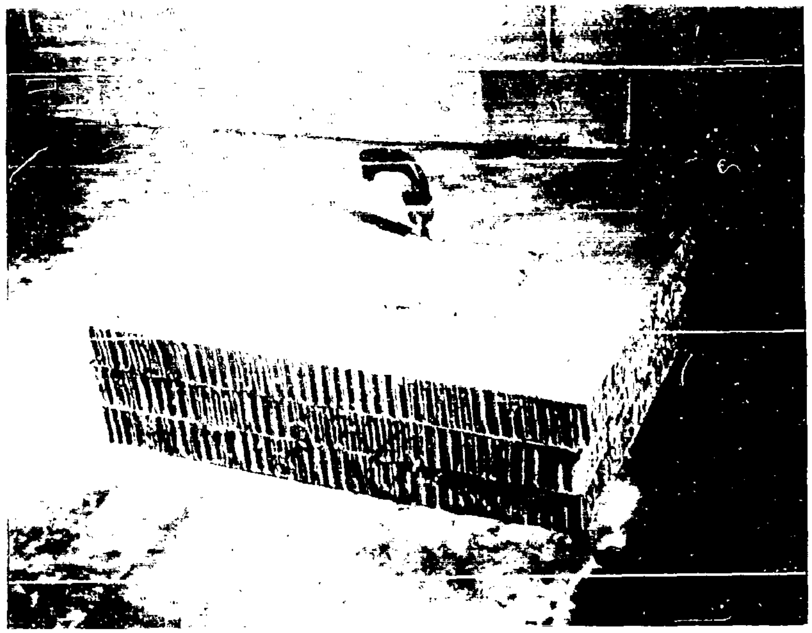


Fig. 7.14. Using a Keyhole Saw to Cut Out the Crushing Area for the Wheels

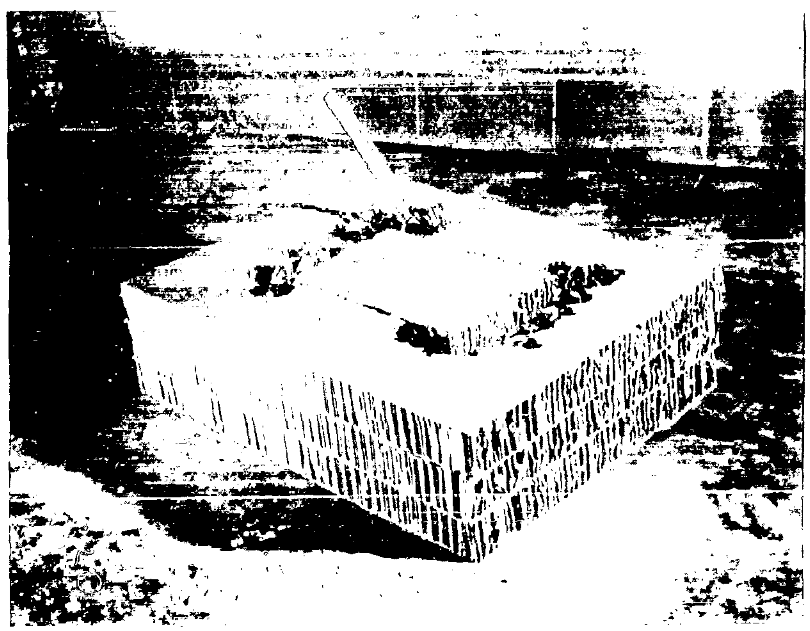


Fig. 7.15. Precrushing Honeycomb Around the Wheel Crushing Area

more than the cut area and causing a higher acceleration as they crush into the stack, precrush a few inches of honeycomb in front and to the rear of the cut area. (See Fig. 7.15)

3. Slide the two 13 x 33-in. central frame stacks, (no. 6 in Fig. 7.10,) under the center of the truck with about a distance of 9 in. between them. Two stacks are used here instead of one large stack because of the type of support available under the truck. The two main frame members down the sides of the vehicle carry more load than does the weaker center cross member. It is desirable, therefore, to place the required cushioning nearer the points of load application, which can be done efficiently with two stacks and one load spreader. Align the front edge of the stacks under the rear edge of the transmission. This should make the front edge of the stacks 33 in. behind the center line of the wheels. Slide the large 35 x 35 x 1-1/2-in. load spreader under the truck on top of the 2 stacks, centering it with the front edge about on the front edge of the honeycomb. If, due to variation in individual truck dimensions, the stack is too high for the load spreader to fit, precrush the top pad of honeycomb with a hammer until the height is right. Sometimes it is easier to install the load spreader on the honeycomb stacks about a foot farther to the rear of the truck, and then slide the three forward together until aligned.

4. Slide the differential build-up stacks, stacks 5 in Fig. 7.10, under the differentials, and glue the smaller crushing stacks, stacks 3 and 4, to their respective build-up stacks in a position directly under each differential.

5. Position the build-up stack, stack 2, for the front cross member between the two platform stacks, and center the crushing stack, stack 1, on the build-up stack, glueing them together when positioned. Slide the load spreader under the front cross member and onto the crushing stack, making sure that the load spreader will not interfere with the spring shackles when they come down. Glue the load spreader to the crushing stack, making sure that all the crushing stack is covered by the load spreader.

6. Position the build-up for the rear cross member, stack 8, between the platform stacks and under the rear cross member. Position the crushing stack, stack 7, on the build-up and slide under the rear cross member. When the position has been marked, glue the two stacks together. Slide the load spreader onto the crushing stack and glue into position. Be sure that the load spreader is far enough to the rear so as not to interfere with the fuel-tank drain plug.

7. Tie the vehicle down tightly.

8. After the drop, the vehicle should come to rest just high enough to clear the honeycomb pads and load spreaders. This results from the fact that the tires deflect during impact and then

raise the frame off the cushions as they regain their original shape after impact. Fig. 7.16 shows the clearance of the frame above the center frame stack for the 3/4-ton truck after impact. It appears that only two honeycomb pads have been crushed, but it must be borne in mind that the build-up pads for this stack are the same size as the crushing pads. As a result, some of the lower pads also crushed, but are hidden in Fig. 7.16. Slide the load spreaders out and remove the honeycomb before driving off. If the vehicle is not clear of the honeycomb after the drop, drive the vehicle a few inches up out of the holes that the tires crushed in the platform pads. This procedure will allow the honeycomb stacks to be removed before continuing to drive off the platform.

Fig. 7.16. Center Frame Clearing Load Spreader After Drop Allowing Stack to be Removed Before Driving Vehicle Off.

The above considerations apply specifically to the 3/4-ton cargo truck, but the principles involved may be applied to the cushion design for any vehicle. The shape of the vehicle, the location of frame members, the weight distribution, the position of heavy or fragile components, all have a bearing on the particular cushion configuration which might be designed for a vehicle. The theoretical calculations must always be tempered with practical requirements in order to come up with a successful cushioning system.

The design of cushioning systems for other military vehicles are discussed in detail in Fragility Studies, Part I,[15] Part III,[17] and Part V.[19] A study of these reports would be quite helpful in predicting and overcoming the problems which arise when designing a cushioning system.

BIBLIOGRAPHY

1. Karnes, Charles H., James W. Turnbow, E. A. Ripperger, and J. Neils Thompson, High-Velocity Impact Cushioning, Part V, Energy-Absorption Characteristics of Paper Honeycomb, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, May 1959.

2. Matlock, Hudson, E. A. Ripperger, James W. Turnbow, and J. Neils Thompson, High-Velocity Impact Cushioning, Part II, Energy-Absorbing Materials and Systems, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, August 1957.

3. Gretz, John L., "Engineering a Cushioned Package," Flow Magazine, Vol. 7, April 1952, (also Modern Packaging, Vol. 25, pp 125-133).

4. Karnes, Charles H., James W. Turnbow, E. A. Ripperger, and J. Neils Thompson, High-Velocity Impact Cushioning, Part IV, The Effect of Moisture Content and Impact Velocity on Energy-Absorption Characteristics of Paper Honeycomb, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, May 1959.

5. Hopf, J. P., Equilibrium Moisture Content of Paper Honeycomb and its Effect on Energy Absorption, Forest Products Laboratory, Project No. 7-87-03-004B, Report No. 1, December 1955.

6. Shield, Richard and Clarke Covington, High-Velocity Impact Cushioning, Part VI, 108C and 100C Foamed Plastics, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, September 1960.

7. Turnbow, James W., Cushioning for Air Drop, Part VII, Characteristics of Foamed Plastics Under Dynamic Loading, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, March 1957.

8. Ali, Ahmin, Cushioning for Air Drop, Part VIII, Dynamic Stress-Strain Characteristics of Various Materials, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, June 1957.

9. Morgan, Carl W. and Walter L. Moore, Cushioning for Air Drop, Part V, Theoretical and Experimental Investigations of Fluid-Filled Metal Cylinders for Use as Energy Absorbers on Impact, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, December 1956.

BIBLIOGRAPHY

(Cont'd)

10. Ali, Ahmin and Hudson Matlock, Cushioning for Air Drop, Part VI, Preliminary Investigation of the Absorption of Shock Energy by Wood in L teral Compression, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, March 1957.

11. Luke, Robert R., The Impact Response of a Single-Degree-of-Freedom System with Viscous Damping, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, June 1960.

12. Richter, Albert P., Jr., The Response of a Two-Degree-of-Freedom Undamped System Subjected to Impulsive Loading, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, August 1960.

13. Huckabay, James D., A Study of the Plastic Deformation of a Single-Degree-of-Freedom System Subjected to Impulsive Loading, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, September 1960.

14. Army Regulation 705-35, Research and Development of Material, Criteria for Air-Transportability and Air Delivery of Material, Headquarters, Department of the Army, Washington 25, D. C., 26 February 1960.

15. Covington, Clarke, Robert R. Luke, Albert P. Richter, and Richard Shield, Fragility Studies, Part I, Utility Truck, 1/4-Ton, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, March 1960.

16. Covington, Clarke and Richard Shield, Fragility Studies, Part II, Cargo Truck, M37, 3/4-Ton, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, April 1960.

17. Covington, Clarke and Richard Shield, Fragility Studies, Part III, Cargo Trailer, M100, 1/4-Ton, 2-Wheel, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, May 1960.

18. Shield, Richard, and Clarke Covington, Fragility Studies, Part IV, Cargo Trailer, M101, 3/4-Ton, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, August 1960.

19. Shield, Richard and Clarke Covington, Fragility Studies, Part V, Water Tank Trailer, XM 107E2, 1-1/2-Ton, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, September 1960.

BIBLIOGRAPHY

(Cont'd)

20. Fowler, Wallace, An Analytical Study of an Undamped Nonlinear Single-Degree-of-Freedom System Subjected to Impulsive Loading, Austin, Texas, Structural Mechanics Research Laboratory, The University of Texas, To be released approximately January 1, 1962.

APPENDIX

PROPOSED

MILITARY STANDARD

AIR DELIVERY LOADING ENVIRONMENT AND RELATED REQUIREMENTS FOR MILITARY MATERIEL

FSC 1670

PROPOSED MIL-STD (QMC)

ARMED FORCES SUPPLY SUPPORT CENTER

WASHINGTON 25, D. C.

Air Delivery Loading Environment

And Related Requirements for Military Materiel

MIL-STD

1. This standard has been approved by the Department of the Army and is mandatory for use by the Department of the Army effective * __________.

2. Recommended corrections, additions, or deletions should be addressed to the Standardization Division, Armed Forces Supply Support Center, Washington 25, D. C.

* NOTE: This draft, dated 16 Oct 1961, prepared by the Quartermaster Corps, has not been approved and is subject to modification. DO NOT USE PRIOR TO APPROVAL.

FOREWORD

Several general guidance documents are in effect in the Army covering technical information and operational air delivery requirements for military equipment. However, until recently, effort to provide such information to design engineers, during the engineering design phase of an end item's development cycle, has been quite limited.

In general, air drop requirements for an item are given consideration after the test prototypes are completed. This is particularly pertinent to standard commercial items that are procured for military use with little or no modification. Then, by utilizing the available provisions and structural members of the item, supplemented by field modifications which add special hardware components and local reinforcements, the item is adapted to the air drop environment.

It is recognized that economical and operational benefits accrue by considering the air drop requirements during design phases of materiel or for commercial items in the fabrication phase.

As the number of items requiring air delivery becomes larger, the need for reference publications covering detailed technical air delivery design criteria becomes increasingly acute. To meet this need, the Quartermaster General (assigned responsibility by Army Regulation AR 705-35 with preparing, coordinating and conducting the Army's research and development program on air delivery equipment) has prepared this standard for Army wide use in the procurement of commercial items, and the design of military

equipment having an air delivery requirement.

Other publications are under active consideration and will be made available as the state of the art progresses.

PROPOSED MIL-STD (QMC)

CONTENTS

PARA.		PAGE
1.	Scope	94
2.	Referenced Documents	94
3.	Definitions	94
4.	General Requirements	95
4. 1	Loading Conditions due to Air Delivery Environments	95
4. 1. 1	Item Restraint	96
4. 1. 2	Extraction	96
4. 1. 3	Recovery	96
4. 1. 4	Ground Impact	96
4. 2	Engineering Assistance	96
4. 3	Suitability and Acceptance of Air Delivery Provisions	97
5.	Detailed Requirements	97
5. 1	Loading Developed on Ground Impact	97
5. 2	Energy Dissipater	97
5. 3	Application of Energy Dissipater	97
5. 4	Airdrop Impact Test (Simulated)	98
5. 4. 1	Detailed Test Procedures and Requirements	99
5. 4. 1. 1	Rigging Item for Test	99
5. 4. 1. 2	Preparing Energy Dissipater Stacks	99
5. 4. 1. 3	Test Requirements	99
5. 4. 1. 4	Instrumentation	100
5. 4. 1. 5	Documentation	100
5. 4. 1. 6	Suitability and Acceptance	100

FIGURES

Figure 1 - 3/4-Ton Truck Ready for Drop Tests (Two Views)

Figure 2 - Positioning of Paper Honeycomb Stacks to Provide Drive-On or Tow-on Capability (Two Views)

APPENDIX

ENERGY DISSIPATER CONFIGURATION DESIGN EQUATIONS

PROPOSED MIL-STD- (QMC)

1. Scope. - This standard defines the various loadings that Army materiel experience when airdropped, references related documents containing essential design considerations and establishes a method to determine and evaluate the ability of materiel to withstand the ground impact resulting from an actual airdrop.

2. Referenced Documents

2.1 The issue of the following documents in effect on the date of invitation for bids form a part of this standard to the extent specified herein:

SPECIFICATIONS

MILITARY

MIL-H-9884 - Honeycomb, Material, Cushioning, Paper.

STANDARDS

MILITARY

MIL-STD______ - Requirements for Tiedown, Suspension and Extraction Provisions on Military Materiel for Air Delivery.

3. Definitions

a. Air Delivery. - A method of air movement wherein personnel, supplies, and equipment are unloaded from aircraft in flight. Synonymous with airdrop.

b. Item Weight. - Weight of item, in its air delivery configuration, exclusive of rigging components such as parachutes, tiedowns and platforms.

c. Energy Dissipater. - As used in this standard, a crushable material used to dissipate kinetic energy during impact.

d. Load Spreader. - A device for increasing the bearing area of a concentrated load. As applied in this standard, it may be used between

a wheel, frame, or other member and the energy dissipater to assure crushing of the desired dissipater area.

e. Suspension Provision. - An integral part of an item used as a means for attaching a suspension sling.

f. Tiedown Provision.- An integral part of an item such as a pad with eye, shackle, ring or other device for use in attaching a tiedown device to the item.

g. Extraction Provision. - A provision integral to an item on the forward or aft end for use in attachment of the extraction system.

h. "Drive-on" "Drive-off" Capability. - Capability to drive a vehicle on or off the energy dissipater stacks without using an external power source.

i. "Tow-on" "Tow-off" Capability. - Capability to tow a vehicle on and off the energy dissipater stacks using an external power source.

j. Recovery System. - A system consisting of recovery parachute (s), riser extensions, load suspension slings and necessary coupling hardware used to retard and stabilize the descent of an air drop item.

4. General Requirements. -

4.1 Loading Conditions Due to Air Delivery Environments. - It is essential that materiel, i.e., items airdropped to combat forces, be capable of immediate effective employment. Any airdropped item, from the time it is put in an aircraft until it is recovered and placed in operation on the ground, will have been subjected to a loading environment due to the following conditions:

a. Restraint of the item in the aircraft for flight safety.

b. Unloading of the aircraft in flight by parachute or other

extraction method.

c. Deployment of the parachute recovery system.

d. Deceleration at ground impact.

4.1.1 Item Restraint. - To prevent displacement of materiel while in the aircraft. Tiedown provisions (attachment devices) on the item shall conform to requirements of MIL-STD______.

4.1.2 Extraction. - To provide for attachment of the extraction system. This extraction provision shall conform to the requirements of MIL-STD____.

4.1.3 Recovery. - To provide for attachment of the parachute recovery system, parachute suspension provisions shall conform to the requirements of MIL-STD______.

4.1.4 Ground Impact. - To provide the maximum protection to materiel against damage on ground impact, the item shall be designed to accommodate energy dissipaters currently in use. For an item whose design is fixed, the energy dissipaters shall be selected to conform as required. Detailed requirements covering the use of energy dissipaters and establishment of tests necessary to determine that the materiel, when used with the dissipaters, will sustain the loading developed on ground impact are set forth in Section 5 below.

4.2 Engineering Assistance. - Engineering assistance pertaining to use of this standard shall be obtained from the US Army Quartermaster Research and Engineering Command, Natick, Massachusetts. The ground impact tests required by paragraph 5.4 may be performed at contractor or Government facilities as specified by the contracting officer. When a Government test facility is used, the contractor shall

pay all expenses and perform all functions pertinent to the conduct of the test with the following exception: The Government shall provide the instrumentation and required operating personnel. All other requirements incident to supplies and personnel for preparation and evaluation of the item prior to and subsequent to drop tests shall be the responsibility of the contractor.

4.3 Suitability and Acceptance of Air Delivery Provisions.- Final approval of the location and number of air delivery provisions as set forth in sections 4.1.1, 4.1.2 and 4.1.3 above is the responsibility of the contracting officer.

5. Detailed requirements. -

5.1 Loadings Developed on Ground Impact. - The item shall be capable of withstanding a deceleration force level of 19.5 (plus or minus 10 per cent) times its weight when decelerated from a velocity of approximately 25 ft per sec to zero ft per sec on ground impact (see Appendix, paragraph 10.1), and meet the performance requirements of the end item specification when tested in accordance with paragraph 5.4.

5.2 Energy Dissipater. - The energy dissipater shall be paper honeycomb, Class 3, Style A of MIL-H-9884, commercially designated as 80-0-1/2, expanded double-faced, 3 inches thick panel. (This dissipater crushes at an essentially constant dynamic stress of 6,000 pounds per square foot (plus or minus 10 per cent) through 0 to 70 percent strain. Crushing stress rises rapidly beyond 70 percent strain.)

5.3 Application of Energy Dissipater. - Energy dissipaters shall be

used in the minimum number of stacks commensurate with the area of the dissipater required, the bottom configuration of the item, and the structural strength of the item. The stacks shall be selected and arranged to permit the item to be placed on the stacks with the least amount of mechanical handling equipment. If it is a wheeled or tracked item, the dissipater configuration shall permit "drive-on" "drive-off", "tow-on" "tow-off" capability.

5.4 Airdrop Impact Test (Simulated). - A simulated airdrop impact test shall be conducted to demonstrate that the energy dissipater has been satisfactorily distributed and that the item can meet the deceleration requirement of paragraph 5.1 and still meet the peformance requirements of the end item specification (see paragraph 5.4.1.6). In general, the requirements of paragraph 5.1 will be met by using 3.1 sq ft of paper honeycomb crushing area for each 1000 pounds of weight of item and a total thickness of 9 inches of paper honeycomb composed of 3 layers of 3-inch thick pads. Under these conditions, duration of deceleration force is 40 to 50 milliseconds depending upon the energy absorption characteristics of the load. With physically large built-up items such as vehicles, the bearing area of the dissipater necessary to produce 18.5g deceleration (see Appendix, paragraph 10.4) is usually much less than the under surface area of the item. In these cases, the item must not only withstand the dynamic compressive stresses at impact, but must also withstand the stresses due to the relative motion of the various parts of the item. Thus, consideration must be given to the distribution of the dissipater area on the under surface of the item as well as the total area of energy dissipater used (i.e., the force input).

Test drops shall commence with decelerating force levels lower than specified while retaining a total thickness of nine inches to preclude any initial extensive damage to the test item. The equations of the appendix shall be used in determining impact velocities and areas of energy dissipater stacks for force levels other than specified in paragraph 5. 1. When item height and aircraft clearance requires a reduction in the thickness of the dissipater, the equations of the appendix may be used in determining areas and force levels.

5.4.1 Detailed Test Procedures and Requirements. -

5.4.1.1 Rigging Item for Test. - The test item shall be placed on the selected energy dissipater stacks under which will be a wood or other approved skid or platform to provide a strong uniform surface for the stacks. Typical wheeled vehicles, rigged for such a test, are illustrated in Figures 1 and 2.*

5.4.1.2 Preparing Energy Dissipater Stacks. - In preparing the item for the simulated airdrop impact test, and where the underneath side of the item in contact with the top of the energy dissipater stack does not present a flat contact surface, a wood load spreader shall be provided. This load spreader shall be of sufficient thickness to insure full crushing of the stack over its entire area. Load spreader and layers of paper honeycomb shall all be glued together and to the skid or platform to prevent shifting, sliding or the like.

5.4.1.3 Test Requirements. - The test shall be conducted using a

---

*These figures are omitted here. See Figs. 7.7, 7.10, 7.11, and 7.12 of this report.

concrete impact surface. The requirement of 25 ft per sec ground impact velocity specified in paragraph 5. 1 will be considered attained when the item is free dropped from a height of 10 ft measured between the bottom of the skid or platform and the impact surface. Dissipater configuration shall be designed to produce the minimum rebound. Rebound can be minimized by placing as much of the dissipater area as is practical under rigid frame members.

5. 4. 1. 4 Instrumentation. -

a. High-speed motion pictures of the impact phase of the drop shall be obtained for the two record drops required by paragraph 5. 4. 1. 6. Nominal frame rate may vary from 2000 to 4000 frames per second.

b. If requested by the contracting officer, strain gage and permanent deformation data shall be obtained at those locations which appeared to be overstressed in previous tests.

5. 4. 1. 5 Documentation. - Six glossy photographs (8 x 10 inches) of each view; front, rear, side and diagonal, of the selected dissipater stack layout, with and without the item on the stacks, and one reproducible engineering drawing showing a dimensioned plan and elevation layout of the energy dissipater configuration are required for review and record.

5. 4. 1. 6 Suitability and Acceptance. - The number of preliminary drops at reduced force levels is the choice of the contractor. However, performance during two final record drops, at the force level specified in paragraph 5. 1, shall constitute the test from which the Government will accept or reject the item. Performance of the item after each of

the two drops shall be demonstrated by operation. The quality assurance provisions of the end item specification shall control. However, in general, evidence of permanent deformation or displacement of components or failure to function properly will be cause for rejection of the item.

Notice. - When Government drawings, specifications, or other data are used for any purpose other than in connection with a definitely related Government procurement operation, the United States Government thereby incurs no responsibility nor any obligation whatsoever; and the fact that the Government may have formulated, furnished, or in any way supplied the said drawings, specifications, or other data is not to be regarded by implication or otherwise as in any manner licensing the holder or any other person or corporation, or conveying any rights or permission to manufacture, use, or sell any patented invention that may in any way be related thereto.

Copies of specifications and standards required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer.

Copies of this standard for military use may be obtained as indicated in the foreword to the Index of Military Specifications and Standards.

Copies of this standard may be obtained for other than official use by individuals, firms, and contractors from the Superintendent of Documents, U. S. Government Printing Office, Washington 25, D. C.

Both the title and identifying symbol number should be stipulated when requesting copies of military standards.

Custodians:	Other Interests:	Preparing Activity:
Army - QMC	Army - CE & Ord	Army - QMC

APPENDIX - ENERGY DISSIPATER CONFIGURATION DESIGN EQUATIONS

10. This appendix is a summary of the equations used to calculate numerical values required in design of energy dissipater configurations and in preparing for ground impact tests.

10.1 To find dissipater area to develop a specific decelerating force level:

Decelerating Force Level, lbs = W(G plus 1)

$$A = \frac{W(G \text{ plus } 1)}{S_a}$$

A = dissipater area, sq ft

W = weight of item in test, lbs.

G = number of "g's" deceleration

S_a = average dynamic crushing stress of dissipater, pounds per sq ft

10.2 To find impact velocity for lower force level tests:

$$V^2 = 2gGEt$$

t = thickness, feet

g = 32.2 = acceleration due to gravity

E = material thickness efficiency = 0.7

10.3 To find free drop height to develop a specific velocity on ground impact:

$$h = \frac{v^2}{2g}$$

h = free drop height (ft) required to develop V at ground contact

V = velocity desired, ft/sec

10.4 The minimum final design value of 18.5 has been selected for "G".

Selection of this value was based upon investigating standard military vehicles under tests outlined herein and the observation that all items that were able to pass these tests were successfully air delivered.

AD ______________ Accession No. ______________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O.I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the 'state of the art' of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

AD ______________ Accession No. ______________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O.I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the "state of the art" of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

AD ______________ Accession No. ______________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O. I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the 'state of the art' of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable 'one-shot' materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

AD ______________ Accession No. ______________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O. I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the "state of the art" of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-CM-1383

AD ____________ Accession No. ____________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O. I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the "state of the art" of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

AD ____________ Accession No. ____________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O. I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the "state of the art" of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

AD ____________ Accession No. ____________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O. I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the "state of the art" of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

AD ____________ Accession No. ____________

Structural Mechanics Research Laboratory
The University of Texas, Austin, Texas

Design of Cushioning Systems for Aerial Delivery of Equipment - Billy C. Ellis, E. A. Ripperger, and J. Neils Thompson

August 1961, 113 pp - figures
(Contract DA 19-129-QM-1383, Task IV)
O. I. No. 9118
Unclassified Report

This report is a summarization and recapitulation of information presented in more detail in previous Structural Mechanics Research Laboratory reports. It is in essence a report on the "state of the art" of aerial-delivery practice. Basic principles of cushioning for aerial delivery using crushable "one-shot" materials are discussed. This includes consideration of design criteria based on the ruggedness, or lack of ruggedness (fragility) of the item to be cushioned, and the characteristics of the applied shock. Dynamic stress-strain curves are presented for a number of materials which have potential application to the aerial-delivery problem. The design of cushioning systems in general, using paper honeycomb, is discussed and several illustrative examples are presented of cushioning systems which have been successfully used in simulated air drop. A proposed Military Standard for aerial delivery is appended.

Unclassified

1. Cushioning Systems - Aerial Delivery
2. Contract DA 19-129-QM-1383

UNCLASSIFIED

UNCLASSIFIED